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STARLIGHT

HARLOW SHAPLEY

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BY

HARLOW SHAPLEY
DIRECTOR OF THE HARVARD OBSERVATORY

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PREFATORY NOTE

In this essay an attempt is made to present the modern scientific view of the place of man and man's earth in the expanse of time and space revealed by discoveries of modern astronomy. Many of the matters discussed are of such recent development that textbooks do not include them; and in some of the fields considered the activity is so marked that ten years hence an essayist may consider the present treatment as obsolete as the essays of twenty years ago now appear to us.

It is a fortunate characteristic of astronomy, perhaps because it is an old and familiar science, that its results and progress can be described in non-technical language. We are all familiar with much of its small special glossary, including such words as stellar and solar, nebula and galaxy, spectrum and spectroscope, latitude and longitude. The technicalities that have more recently crept in are mainly due to the astronomer's increasing use of the methods and vocabulary of the related sciences of physics, chemistry, geology, and statistics.

The fundamental simplicity in the ideas as well as in the language of astronomy will permit a treatment of recent important scientific

advances, even though this essay is designed primarily for the general reader and not in the least for the professional astronomer.

After making, in Part I, a general survey of the field, it is proposed to take up two of the most fascinating subjects of modern astronomy: the evolution of stars, including the origin of the earth and other planets; and the measurement of the dimensions of the stellar universe.

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I

CONCERNING CONSTELLATIONS AND BRIGHT STARS

THE three astronomical bodies of which we are all continually aware—the earth, the sun, and the moon—afford good illustrations of different stages in universal evolution. The earth is a typical small planet whose life history records the course of development of similar small parts of the physical universe. The sun is a fairly typical star—a volume of mixed gases at enormously high temperatures. A description of its structure and probable past history outlines for us the nature and evolution of millions of other stars. The moon is a satellite, in many ways typical, an attendant upon a planet that is itself dependent on a star.

Although we are sure of the existence of millions of bodies comparable with the sun, the only planets of whose existence we can be certain are the eight that compose the solar

family; and the only moons we know are those circling around the planets of our sun.

Of the celestial bodies that, after the sun and moon, *appear* to us most conspicuous in the sky, some are members of the primary and some of the secondary class—that is, many are suns, a few are planets. Some are stars that either are exceedingly powerful as light producers or appear to be powerful because near at hand, as star distances go. Others are planets, relatively small and physically unimportant compared with stars, but bright (in the light they reflect from the sun) solely because of their nearness to the earth.

Although the brighter stars and planets look much the same to the unaided eye, a telescope shows that the planets have visible surfaces (disks), whereas the stars, though enormously larger, always appear as points of light because of their excessive distance. The telescope magnifies the brightness of stars to the extent that its aperture exceeds the aperture of the unaided eye; but no telescope magnifies the size enough to make a star's surface perceptible.

It is interesting to digress here for a paragraph to notice that the brightest appearing celestial object (aside from sun and moon) is Venus at favorable phases—a planet that is

smaller even than our earth and shines only by reflected sunlight. In contrast to Venus, some of the stars recently discovered in a distant star-cloud, through a study of photographs made at the Harvard Observatory, are more than 100,000,000,000,000 times more radiant than Venus at her best; but these giant stars, on account of great distance, appear so faint that it takes a good telescope to detect them.

Stellar Magnitudes

The stars can be readily arranged in approximate order of brightness. The light is commonly expressed in *magnitudes.* Each star of the first magnitude is, by definition, one hundred times as bright as a star of the sixth magnitude, which is about the limit for the naked eye. All intervening grades of brightness are found, and below the sixth magnitude the telescopic stars extend indefinitely fainter. Twenty of the brightest stars are classed in the first magnitude. The following list gives the designation, using a Greek letter and the name of the constellation to which the star belongs, and also it gives the individual name. The distances are given in light-years, that is, in units of 5,870,000,000,000 miles, and the more uncertain values are indicated with colons. The inherent luminosity of each star is com-

puted from the observed apparent magnitude and the distance, and is expressed in terms of the light power of the sun.

Constellation and Name		Apparent Visual Magnitude	H.D.C. Spectrum	Distance	Luminosity (Sun = 1)	
α Canis Majoris	= Sirius	—1.58	A0	9	26	Visible in early winter evenings
α Aurigae	= Capella	0.21	G0	52	170	
β Orionis	= Rigel	0.34	B8p	540:	17,000:	
α Canis Minoris	= Procyon	0.48	F5	10	6	
α Orionis	= Betelgeux	0.92	Ma	190	1,200	
α Tauri	= Aldebaran	1.06	K5	57	100	
β Geminorum	= Pollux	1.21	K0	32	27	
α Bootis	= Arcturus	0.24	K0	40	105	Visible in late winter evenings
α Virginis	= Spica	1.21	B2	360:	3,400:	
α Leonis	= Regulus	1.34	B8	56	70	
α Lyrae	= Vega	0.14	A0	26	48	Visible in summer evenings
α Aquilae	= Altair	0.89	A5	16	9	
α Scorpii	= Antares	1.22	Ma	125	3,300	
α Piscis Austrini	= Fomalhaut	1.29	A3	24	13	
α Cygni	= Deneb	1.33	A2p	650:	10,000:	
α Carinae	= Canopus	—0.86	F0	650:	75,000::	Southern Hemisphere
α Centauri		0.33	G0	4.3	1.1	
α Eridani	= Achernar	0.60	B5	67	200	
β Centauri		0.86	B1	90	300	
α Crucis		1.05	B1	110	350	

Just fainter than these leading stars are such objects as the three stars in the belt of Orion, and the north star, Polaris. They are of the second magnitude, which includes about three times as many stars as the first. The

third magnitude includes nearly three times as many stars as are found in the second; and similarly, with each fainter magnitude, the number of stars triples, or at least doubles, to the twenty-first magnitude, which is near the limit reached photographically by the greatest telescopes. With the greatest visual telescope the limit is somewhere near magnitude seventeen.

The Number of Stars

One fact immediately strikes our attention. *The stellar universe is almost entirely telescopic.* Only a minute part is within the reach of unaided human sight. Five thousand stellar objects are in the first six magnitudes. Before the telescope was perfected, man's knowledge of the universe was therefore confined to the relatively small region of the nearer and brighter stars. With increase of instrumental power and the development of photography, he has reached to unsuspected depths and now knows of a million times as many stars as were known by his not very remote forbears.

Aristotle probably never saw more than four thousand stars in his life. Nowadays a single photograph with a Harvard telescope frequently shows, in a small section of the sky, more than five hundred thousand stars! Moreover, we have every reason to believe that beyond the limits reached by our present telescopes and photographic plates there are

billions of unrecorded luminous stars and nebulae.

Star Groups

Returning to our brief statement concerning the brighter stars, attention should be called to the groupings or constellations. The names and boundaries for many constellations are inherited from the days of classical mythology. The fanciful names and figures have, of course, no material significance, but some of the stars grouped together on the surface of the sky are actually associated in space. Their relative positions are not solely an accident of projection. Five of the bright stars of the Big Dipper, for instance, form a real organization which also includes Sirius; and most of the bright stars in Orion are closely allied with each other.

The astronomer no longer attempts to locate a star by means of a description of its place in a constellation—by the statement, for instance, that it is in the head of Hercules or in the tail of the Dragon. He uses, instead, a pair of position coördinates, such as declination and right ascension, which exactly indicate the place on the surface of the sky. In much the same way, the professional botanist, describing a plant, uses a technical term of definite connotation, rather than some loose popular name.

Although the names themselves generally

A region of the Southern Milky Way. Photographed at Arequipa by Miss Harwood. In the center is the Coal Sack (a large dark nebula) and adjoining it are the four stars that form the constellation of the Southern Cross. The bright star at the extreme central left is Alpha Centauri, the sun's nearest neighbor.

are of limited scientific use, nevertheless the identification by name and position of a few of the constellations, stars, and stellar groups should be a part of the knowledge of everyone at all interested in science. Sirius should be as familar as the buttercup, and Polaris as readily identified as a crow. We should know at least the constellations Orion, Ursa Major (the Big Dipper), Ursa Minor, Cassiopeia, Cygnus, Aquila, Pegasus, and Scorpio; the Pleiades and the Hyades; the Orion nebula, the Andromeda nebula, and the Hercules cluster; Polaris, the variable star Algol, and the first magnitude stars listed above. Passing knowledge of these details is easily gained with the aid of a star chart, and gives the possessor a sudden and astonishing familarity with the whole subject matter that the astronomer deals with in discussing the evolution of stars and planets and the measurement of sidereal space.

Motions of Stars and Planets

The brighter planets can be observed slowly shifting their positions with respect to the stars and to each other, owing to their own motions and the motion of the earth around the sun. Venus, Mars, Jupiter, and Saturn are the only ones commonly seen, as Mercury is too close to the sun for easy observation and Uranus and Neptune are too faint. In striking contrast to these easily observed planetary motions is the apparent fixity of the stars, for although they

are known to have high velocities of their own, and although the earth and sun are also moving rapidly through space, the distances separating stars and solar system are so great that the stellar configurations throughout centuries remain, except for a few minor details, just as we see them now.

Stellar Luminosity

Among the few thousand stars visible without a telescope there is a great diversity in candle power and a large range in distance from the sun, as illustrated in the preceding tabulation. Some of the first magnitude stars, such as Sirius and Alpha Centauri (the first being the brightest of stellar objects and the second being the nearest), *appear* highly luminous because of their relative nearness to the sun and earth, though their intrinsic luminosities are not abnormally high. Others, such as Betelgeux and Antares, though very far away, are also first magnitude stars because their actual candle powers are exceedingly high. As a further illustration we may note that Rigel, one of the conspicuous stars in the great quadrilateral of Orion, is more than one hundred times as far from us as Alpha Centauri; but it *appears* almost exactly as bright as that star because the dimming effects of its greater distance are counteracted through the circumstance that Rigel's candlepower is more than

ten thousand times as great. Alpha Centauri is, in fact, much like the sun in luminosity.

We must therefore carefully distinguish *apparent* brightness from *real* or inherent brightness. The apparent brightness, generally called apparent magnitude, may be measured either visually or photographically and depends on the distance from the earth as well as on light emission. The real brightness is called absolute magnitude, or, popularly, candle power, and is, of course, independent of distance from the observer. Its measurement is a much more difficult problem and one that astronomers have only recently treated with partial success.

II

IN THE SOLAR NEIGHBORHOOD

IN THE part of space that we may call the neighborhood of the sun, there are hundreds of stars invisible to the unaided eye for every one we see. Our numerous telescopic neighbors are dwarfish, and many, no doubt, have not yet been detected or recognized by the telescope or photographic plate.

The Sun as a Star

But although the region near the sun contains much that we do not know, it also contains many representative types. Brief comments on some of the better known stars of the neighborhood may serve as a general introduction to the discussion in later chapters.

The sun, first of all, may be treated as a star. It is typical of a large class. An extensive star catalogue* recently completed at the Harvard Observatory contains the positions and de-

* The Henry Draper Catalogue, described in Chapter IV.

scription of 20,000 stars so nearly like the sun that no conspicuous differences could be found with the means at hand. The diameter of the sun is 868,000 miles—considerably less than the diameter of the average of the naked-eye stars (which are mainly giants), but nearly equal to the diameter of the average dwarf.

The temperature of the sun at the surface is about 10,000 degrees Fahrenheit, but inside the temperature is believed to rise to millions of degrees. The sun's yellowish color is intermediate between the blue-white of the hottest stars and the reddish tint of those with cooler surfaces. An analysis of sunlight with the spectroscope†—that most important of astronomical instruments—shows that the hot vapor at the sun's surface is composed of the atoms of the same chemical elements that appear on the surface of the earth. We find, in particular, such familiar substances as hydrogen, oxygen, zinc, carbon, iron, and nickel. No element is known in the sun that is not found on the earth.

The material of the solar system is practically all concentrated in the sun. The mass of the eight planets with their moons, of the comets and the meteors, of the swarm of asteroids or minor planets that revolve between the orbits of Mars and Jupiter, is altogether

† See Chapter IV concerning spectroscopes.

less than one-fourth of one per cent of the mass of the sun.

The distance from the sun to the earth, 93,000,000 miles, called the astronomical unit, is a convenient unit in measuring distances in the planetary system. The distance from the sun to Neptune, the outermost known planet, is thirty astronomical units; but this distance is insignificant compared with the distance to the nearest star. Also in dimensions, mass, and reflected brightness all the planets are very minute from the stellar point of view, however important they may appear to us. The sun, however, measures up well in mass, volume, and luminosity with the other dwarf stars of its class.

The Nearest Neighbor

Alpha Centauri, the sun's nearest neighbor, is much like the sun in temperature, size, color, and chemical constitution, but differs in one important respect—it is a double star. To the naked eye the star appears single, but a small telescope shows it to be composed of two nearly equal stars. The components are separated in angular measurement by sixteen seconds of arc. (The diameter both of the sun and the moon in *angular* measurement is about half a degree, which corresponds to thirty minutes of arc, or to 30x60=1800 seconds of arc.) From the known distance of Alpha Centauri, we can easily compute that the angular separa-

tion of sixteen seconds of arc corresponds to a linear separation of about two thousand million miles. The planet Uranus is 1800 million miles from the sun.

The two bodies that compose the system of Alpha Centauri revolve around their common center of gravity in 79 years; the period of Uranus around the sun is 84 years.

Another point of interest concerning the system of Alpha Centauri is the existence of a little companion star at a distance of a million million miles from the brighter pair. This object, discovered by Innes on photographs made in South Africa, is, in absolute magnitude, one of the faintest objects ever found. Its motion through space is the same as that of Alpha Centauri, around which it probably revolves in a period of some thousands of years. There is evidence that at the present time the faint reddish companion is slightly nearer to us than is Alpha Centauri itself; for this reason the dwarf has been named Proxima Centauri. As seen from Alpha Centauri, Proxima would be of the fourth magnitude. If there were such a dwarf companion to the sun, it almost certainly would have been found before this date. But a dwarf solar companion at three times the distance that separates Proxima from its primary might still remain undiscovered, since our critical examinations of the motions and distances of

faint stars is not yet sufficiently complete to eliminate such a possibility.

Units of Distance

The distance from the sun to its three near neighbors in Centaurus is 275,000 astronomical units, or twenty-five trillion miles. In recent years astronomers have adopted another unit for the description of stellar distances and named it the *parsec*. It is equal to 206,265 astronomical units, or nearly 20,000,000,000,000 miles. This unit was chosen for the reason that it corresponds to the distance necessary for an angular length of one second of arc (1″) to correspond to one astronomical unit. That is, for an object one *parsec* distant, the parallax,* or angular measure of distance, is one second.

A kiloparsec, the equivalent of a thousand parsecs, is sometimes used as the unit for the more distant stars and nebulae.

The *light year* is also a unit of stellar distance in common use. It is the distance traveled by light in a year's time and corresponds to nearly six trillion miles. It is therefore a little less than a third of one parsec. Expressed in these units, the distance to the nearest star is 1.3 parsecs or 4.3 light years. An advantage of the light year as a unit is that it indicates time duration as well as distance. It emphasizes, for instance, that

* See Chapter XII, p. 122.

the light now arriving at the earth from Alpha Centauri has been en route for four years and four months.

The "light minute" could well be used as a unit for expressing distances in the solar system. Thus, the distance to the sun is 8.3 light minutes, and the diameter of Neptune's orbit is approximately 500 light minutes. The distance from earth to moon, however, is only 1.2 light seconds, for the velocity of light is about 11,000,000 miles per minute.

Double and Variable Stars

Continuing the cursory examination of the brightest stars, we note that Capella, Sirius, Procyon, and Spica are also first magnitude double stars; but they differ from Alpha Centauri in many respects, such as color, the relative brightness of their components, and the periods of revolution. The condition of being double is obviously common among the stars.

Rigel, in Orion, is notable for its surface temperature, which is probably about 20,000° Fahrenheit, or even higher. As a consequence the light it emits is decidedly bluer than for average stars. But the stars in Orion's belt are still hotter than Rigel, approaching the highest limit known for stellar temperatures.

Betelgeux and Antares are reddish, and exceedingly large. Their diameters are more than 200 times as great as that of the sun; in

fact, they far exceed the earth's orbit in diameter. The existence of such enormous dimensions does not mean that the amount of material in the red giants is extremely large compared with the mass of the sun, but rather it indicates that the density (specific gravity) of the material is very low in these large stars, and consequently that their extensive volumes are occupied by highly rarefied gases. We believe that the density throughout Betelgeux averages much below that of the earth's atmosphere at sea level.

Constancy is not a universal attribute of the sidereal bodies. Polaris is a variable star, with variations chiefly affecting the amount of light it emits; but probably the diameter also varies, and the average color as well. Algol is a famous eclipsing binary star whose brightness changes periodically, because the earthward-bound light of each component is alternately blocked by the other component in the course of their periodic revolutions about the center of gravity. (In much the same way, the moon blocks the sun's light at the time of a solar eclipse.) Since one of the components of Algol is much brighter than the other, only one of the two eclipses that occur during each revolution is conspicuous. Spica is also an eclipsing variable star. The light of Betelgeux varies irregularly, but the cause is not yet known.

Stellar Movements

The velocity of celestial objects with respect to the sun is one of the many valuable kinds of information that is derived with the aid of the spectroscope. The study of the spectrum, however, gives us only a part of the total velocity in space; it gives in kilometers or miles per second the radial velocity, the component of motion along the line of sight, toward or away from the observer. The other component, at right angles to the line of sight, must be obtained in angular measure from determination of positions at different dates. From these two components—the radial velocity and the proper motion—total velocity can be computed, only if the distance is known for the object under consideration so that the angular proper motion can be transformed into linear motion expressed in miles per second in space.

The first magnitude stars show much diversity in total velocity. Arcturus has an unusually great speed—eighty-five miles per second. The sun's velocity with respect to its neighbors is more nearly normal—about fifteen miles a second. The blue stars generally move less rapidly than the red stars; the dwarfs have higher speed than the giants. A difficulty in the measurement of stellar speed is to find suitable reference points. All stars are in motion—some moving together along

parallel paths, but the majority appearing to travel in random directions.

Giants and Dwarfs

From the foregoing comments on bright and near-by stars, we note that among the sun's neighbors there are many types. There are differences in dimensions, temperatures, colors, and motions; some stars are constant in brightness and others like Algol and Polaris are variable; some are double, some are single, and one that we know of—our own—has a system of planets. It is natural to suppose that these types represent different stages in the evolution of gaseous bodies.

Nearly all the stars mentioned in detail are larger and brighter than the sun. We should remember, however, that most of our nearest neighbors are invisible without a telescope. They are dwarf stars, many of them fainter than the sun. A recent investigation by the writer has shown that, in a typical large region of space near the solar system, there are six hundred stars like the sun for every highly-luminous blue-white giant, such as Spica or the hot stars in the belt of Orion. Of sun-like stars we of course see only the nearest without telescopic aid; but giant stars can be seen from over a greater region of space and are therefore likely to deceive the observer into believing that they are frequent in space and a predominant type.

In the next chapter we shall go further into space, and, examining the contents of the Milky Way, find some classes of objects not found in the immediate vicinity of the sun. In studying the Milky Way we shall necessarily deal mostly with the giants, for the distances are so great that the dwarf stars are not easily considered. The giant stars, however, will be of the highest interest, for their study leads us directly to the measurement of the sidereal universe and to theories of universal evolution.

III

THE GALAXY

TO COUNTRY folk, mountaineers, and dwellers in dimly lighted districts, the feature of the night sky that is as fascinating, and almost as conspicuous as the bright stars and planets, is the encircling band called the Milky Way, or Galaxy. In low altitudes, or in populous regions, through the smoky and hazy skies, this zone of light is poorly seen; but on mountain tops its light is so strong that at times faint and diffuse shadows are cast.

Although the Milky Way has long been an attractive subject for mythology and the poets, the attempt to present a rational explanation of the phenomenon dates only from the middle of the eighteenth century. The names of Wright, Kant, Lambert, and Herschel will always be associated with the early speculation concerning the nature of the Milky Way; but the earliest telescopes, long before,

had resolved its hazy light into individual stars, and some vague and fanciful suggestions had been advanced.

Wright and some of his scientific successors believed the Milky Way to be solely an optical phenomenon—that is, the band of light was considered to be the projection on the sky of a great watch-shaped system of stars, as seen from within. This early explanation coincides with the one generally accepted today.

Irregularities of the Milky Way

It was recognized long ago that the Milky Way does not divide the celestial sphere exactly into halves. The part including the north pole of the heavens is slightly larger. This condition can be readily explained by assuming that our point of observation, the solar system, is slightly to the north side of the central plane of the Galaxy. The offset is so small, however, that the central line of the luminous band is but one or two degrees below the circle that divides the celestial sphere into two equal parts.

The Milky Way is inclined at an angle of sixty-two degrees to the earth's equator and to the projection of the equator on the sky. The half of the Milky Way which is readily visible in the north temperate zone runs through the constellations Aquila, Cygnus, Cassiopeia, Perseus, Auriga, Taurus, Gemini, Orion, and some lesser configurations. In the

southern sky the conspicuous constellations Carina, Crux, Centaurus, Scorpio, Sagittarius, and Scutum lie along the Milky Way. The density is very uneven throughout the circuit. In Taurus and Auriga the band is dim and much broken, while in Centaurus, Carina, and Sagittarius it is uncommonly bright. Also in Cygnus and Aquila there are remarkably conspicuous patches.

This unevenness in the brightness of the Milky Way has much significance, but until recently it was too little appreciated. Most of the world's astronomers live and work in the north temperate zone, in latitudes where the brilliance of the southern Milky Way does not continually impress itself upon them. But the prominent regions in Carina and Sagittarius attract the immediate consideration of southern observers.

An interpretation of the inequalities along the Milky Way will be presented later. Meanwhile we may remark that the southern sky is replete with important objects. Not only the most brilliant star clouds of the Milky Way, but also the brightest stars, some of the brightest nebulae, and many peculiar and instructive fainter objects, can be followed to best advantage at a southern observatory.

Southern Observatories

Aware of the importance of studying the southern sky, several of the observatories of

Europe and the United States have established southern stations, or have encouraged the countries of the south to greater astronomical activity. The British, in South Africa and Australia, the astronomers from the United States, in South America, and the government observatories of the Argentine have contributed most during the last half century to our knowledge of the southern sky.

The Lick Observatory of the University of California has long maintained a southern station at Santiago, Chile, where it has assiduously determined the velocities of the brighter southern stars. Similar work has been done at the Cape of Good Hope; and great catalogues of the positions of the bright and faint stars have been produced by the astronomers in Australia, South Africa, and the Argentine. An Egyptian observatory has contributed systematically for a number of years to our knowledge of southern nebulae. The Mexicans, too, have contributed to the work on star positions, though their observatory at Tacubaya is in northern latitude; despite serious civil disturbances, they have continued to map the sky, in co-operation with other nations.

The observatory that has, however, contributed the most to our knowledge of the brightness and classes of southern stars and the constitution of the southern Milky Way is the Boyden station of the Harvard Observatory. It has been located for the last thirty-five

An observatory in the Andes. The Boyden Station of the Harvard College Observatory near Arequipa, Peru.

years at Arequipa, Peru. For the photography of faint stars, a station at high altitude, in a more or less rainless climate, is especially desirable. Before locating at Arequipa, tests of observing sites were made by astronomers from the Harvard Observatory at Pike's Peak in Colorado, at Mount Wilson in California, at Mount Harvard in north central Peru, and at several high altitudes in the desert regions of Chile. Later an expedition was sent to various localities in South Africa to try out the observing conditions, and tests were made in Australia for the Harvard Observatory by officials of the Queensland government.

The photographic telescopes at Arequipa not only cover the whole of the southern sky, but, being only sixteen degrees south of the equator, they reach to the north of the equator and when desired cover more than half of the northern sky as well. The various telescopes at Arequipa are designed for special problems. A frequent photographic patrol is maintained there for the whole southern sky, and for the Milky Way zone in particular. Telescopes at the Cambridge headquarters of the Observatory cover the remaining part of the northern sky. The patrol keeps vigil on several million stars. As a result of this systematic work at northern and southern stations, the Harvard Observatory has a unique collection of stellar photographs now numbering about a third of a million.

The study of the material in the Harvard photographic collection yields information concerning the positions, brightness, variations, motions, colors, distribution, and types of spectrum of great numbers of stars; but because of lack of funds and workers only a part of the material available has been deduced from the plates and analyzed. Photographic collections similar to that of the Harvard Observatory, though now much smaller, and restricted to limited regions of the sky, are being formed at Heidelberg in Germany, at Johannesburg in South Africa, and elsewhere.

Before leaving this introductory discussion of the general galaxy, we should mention that the individual stars that constitute the band of light are invisible to the naked eye. Among these faint stars are many nebulous objects—diffuse nebulae, gaseous nebulae, spiral nebulae—all of which will be mentioned later in some detail. Ever since the time of Immanuel Kant, the spirals have frequently been considered to be other galaxies, comparable to our own great flattened system of stars (see Chapter XIII); and one of the most interesting current problems of astronomy is to decide whether or not spiral nebulae are stellar systems—whether or not we must contemplate a multiplicity of galaxies in the visible universe.

IV

COLORS AND KINDS OF STARS

A CLOSER examination into the various types that make up the flattened galactic system brings out diversity in many properties of the stars, but also reveals evidences of progressive series. Sequences may be noted especially in color, temperature, and spectrum. We have seen that among the brightest stars there is a wide range of color. This is best verified visually by comparing the reddish Betelgeux with other nearby stars in Orion, most of which are bluish white. With the development of the stellar spectroscope, two generations ago, the colors of stars were related immediately to their classes of spectrum.

The Spectroscope

In its least complex form the spectroscope, for stellar studies, is an ordinary telescope with a glass prism in front of the objective. The light from a star, falling on the prism, is

resolved into its component wave-lengths, the red light being deflected least in its passage through the glass wedge, and the blue and violet light the most. The telescope objective forms an image of the resolved light of the star, and this image, the spectrum, may be examined visually with an eye-piece, or photographed on an ordinary commercial plate. The photographic plate, because of its permanence, and its freedom from possible psychological bias, is preferable to visual records.

This simplest form of the stellar spectroscope, called the objective-prism spectrograph, permits the simultaneous photographing of all the stars in a field. The form most commonly used with a large telescope, the slit spectroscope, is designed to deal with only one star at a time; but it may be equipped with suitable accessory apparatus so that the spectrum of a terrestrial source can be photographed for comparison alongside the spectrum of the celestial body. The comparison spectrum then permits, as will be explained presently, the determination of the position of lines in the stellar spectrum, and leads to the measurement of velocities and pressures in stellar atmospheres.

Stars of a reddish color show in their spectra relatively great intensity in the light of longer wave-lengths, while the blue stars have more light concentrated in the blue end of the

spectrum. Simple theory indicates that the higher the temperature, the more the light is concentrated in the shorter wave-lengths and the bluer the color. The spectroscope thus shows the relative surface temperature of the stars and thereby yields information of high importance concerning stellar evolution.

Stellar Atmospheres

One feature of the spectrum of a star, the absorption lines, is of still higher significance than the distribution of light intensity. The light of a star comes chiefly from a region called the photosphere. Outside are cooler layers of gas, all of which must be traversed by the light that we receive. The density and temperature of the gas in the photosphere are sufficiently great that all wave-lengths of light are radiated, but as the radiation comes through the outer atmosphere of the star, it is partially absorbed.

The degree of absorption is far from uniform. The points along the spectrum where the most conspicuous absorption takes place is dependent upon the nature and condition of the material present. In the spectra of Vega and Sirius the principal series of absorption points or "lines" is due to the atoms of hydrogen. For Arcturus, the sun, Capella, and similar stars, the conspicuous absorption is due to many of the metals, such as iron, nickel,

titanium, manganese, and to hydrogen as well.*

Extensive studies of the nature of spectra, by astronomers and physicists, have finally enabled us to assign many of the hundreds of absorption lines in stellar spectra to the atoms of specific chemical elements in a gaseous state. The spectral lines thus become a guide to stellar chemistry. It was early observed that the hottest stars show absorption lines mainly of hydrogen, helium, oxygen, and carbon. In the stars of intermediate temperature the lines can be assigned to many of the common metals. The redder stars show these metallic lines, and also show groups of lines that can be attributed to absorption, not by atoms themselves, but by the molecules of atomic compounds, such as titanium oxide, and the oxides of carbon, zirconium, and possibly of other elements.

Chemistry of Stars

A second important contribution that the spectroscope has made to knowledge of stellar evolution thus becomes apparent. Not only does it tell us about temperatures, but it in-

* There are several general books dealing with the solar atmosphere and its chemistry; for instance, Abbot's "The Sun," and Mitchell's "Eclipses of the Sun." The most recent and comprehensive special book on the subject of solar and stellar chemistry is Miss Payne's "Stellar Atmospheres," published in 1925 as Harvard Observatory Monograph, No. 1.

troduces us to the chemical analysis of stellar atmospheres. We frequently examine objects so far away that it takes the light hundreds or thousands of years to reach the earth, and yet we can say with confidence that they are composed of familiar elements. It has already been mentioned that a Harvard catalogue shows that large numbers of distant stars are chemically very comparable to the sun; and we can go much farther and say that throughout the whole universe the same chemical elements everywhere prevail.

Although most stars differ from the sun in the observed spectral characteristics, we now know that the appearance or non-appearance of specific absorption lines is due not to chemical constitution, which probably is nearly identical for all known stars, but to the temperatures and densities prevailing in the stellar atmospheres. The temperature and spectrum of Sirius and the sun are now widely different; some time in its life-history, however, Sirius will probably have a spectrum identical with the present solar spectrum. The Sirian temperature is now too high for the atoms of iron, nickel, and the other metals in the stellar atmosphere, to be in an efficient absorbing state, though hydrogen is now in an appropriate condition. On the other hand, the conditions at the surface of the sun are not suitable to excite hydrogen and helium atoms to their strongest absorption, but many

Photograph of the spiral nebula Messier 81, in the Big Dipper, taken at Mount Wilson Observatory. This system is probably at a distance of about one million light years.

metallic atoms are suitably excited for the absorption of the photospheric light that pours through.

The earth has no visible radiation of its own; if, however, a random bit of its rocky surface were heated to appropriate temperatures, with definitely prescribed densities and pressures, we could, no doubt, duplicate very closely the spectrum of any star.

Harvard Spectral Classes

On the basis of the absorption lines, astronomers began long ago to put the various stars into classes of spectrum. Vogel in Germany and Secchi in Italy proposed systems of classification. The larger amount of material available at the Harvard Observatory permitted Professor E. C. Pickering and his associates to propose, about thirty years ago, more elaborate and satisfactory classifications of spectra; and the Harvard system is now internationally adopted as the basis for the study of stellar spectra.

Several catalogues and lists of the spectra and magnitudes of the brighter stars have been made at various observatories. The culminating piece of systematic work in classifying stellar spectra, however, is the Henry Draper Catalogue,* which has been recently completed

* Named in honor of an American pioneer worker in stellar spectroscopy. After Dr. Draper's death, Mrs. Draper provided means for supporting a Henry Draper Memorial at Harvard Observatory for the study of the stars.

at the Harvard Observatory. It contains in nine volumes the positions, magnitudes, and spectral classes of two hundred and twenty-five thousand stars. The spectra are grouped into ten main divisions with thirty or forty subdivisions. The whole sky is covered by this catalogue, which includes practically all stars down to the eighth magnitude, and many thousands that are fainter.

The principal divisions of the Harvard classification are given the letters B, A, F, G, K, M, in the order of decreasing temperature and increasing redness. Rigel and Spica are of Class B, Sirius, Vega, and Altair of Class A, Polaris and Canopus of Class F, our own sun and Capella of Class G, Arcturus and Aldebaran of Class K, and Antares and Betelgeux of Class M.* The stars of Classes A and K are the most frequent in the catalogue; the least common are the stars of Class O at the top of the temperature scale and of Classes R, N, and S at the bottom.

Some stars are found to vary in spectral class, especially those like Polaris which are also variable in light. But an overwhelming majority shows the same arrangement and intensity of absorption lines on all photographs, indicating that the evolutionary changes require a time immeasurably long compared with the brief interval that the stars have been under scientific observation.

* See the tabulation in Chapter I.

The classifications of all stars included in the Henry Draper catalogue were made by Dr. Annie J. Cannon of the Harvard Observatory staff, who has specialized in the study of spectra and is recognized internationally as an authority on the subject. The necessary photographs were made with the telescopes at Arequipa in Peru and at Cambridge. A large staff of observers and assistants was necessary to determine and catalogue the positions, magnitudes, and spectra. The finished compilation is outstanding in astronomical science and is a well-deserved memorial to the late director, Professor E. C. Pickering, who inspired the work and planned its details. A general extension of the classification to fainter stars is under consideration.

Star Velocities from Spectrum Analysis

A microscopic examination of the absorption lines in the spectra of stars generally shows that the stellar lines are displaced slightly, toward either the blue or the red, from the normal positions of these lines when produced in a laboratory. This displacement is the source of knowledge concerning the radial velocities of stars. When a star approaches it tends, so to speak, to catch up with the light it is emitting, with the result that the wave-lengths of the light are shortened. On the photograph, therefore, the spectrum and all its lines are slightly displaced toward shorter

wave-lengths, that is, toward the blue. When the star is receding from the observer, the wave-lengths of emitted light are lengthened, and the absorption lines are displaced toward the red with reference to the terrestrial source used for comparison (which is, of course, at rest with respect to the observer's spectroscope).

This shift toward red or blue, known as the Doppler effect, not only tells of the approach or recession of a star, but frequently shows that the star is double—shows that it is receding at one time from the observer and at another time approaching (as it revolves around its companion star)—for the shift is alternately to the red and the blue.

In concluding this chapter, which mainly emphasizes the great importance of the stellar spectroscope, attention may be drawn to the significant fact that stars very similar in spectral class often differ greatly in evolutionary stage and therefore in dimensions. Some red stars are giants, others are dwarfs—a matter we shall consider further in the next chapter, remarking in anticipation that, upon still closer examination of the spectra, the individual absorption lines reveal not only the temperatures, motions, and chemical nature, as outlined above, but they also are useful in sorting out giants and dwarfs. They tell, therefore, something of the dimensions and densities of the stars.

V

STELLAR DIMENSIONS AND MASSES

ALL methods of measuring stellar dimensions are more or less indirect. Double stars and variables furnish some of the important means, and the spectroscope, photometer, and interferometer are instruments employed.

Mention has already been made of the variable star Algol,* a binary whose variation in light is caused by the eclipses which occur as the components alternately cross our line of sight. About two hundred such stars are now known. They differ greatly in some respects —for instance, in the time between eclipses and in the amount of light that is lost each time. Occasionally more than ninety per cent of the light is obstructed at the principal minimum when the brighter of the two components is nearly or completely hidden by its darker companion. Sometimes the primary and secondary minima are of equal depth, in-

* Chapter II, p. 33.

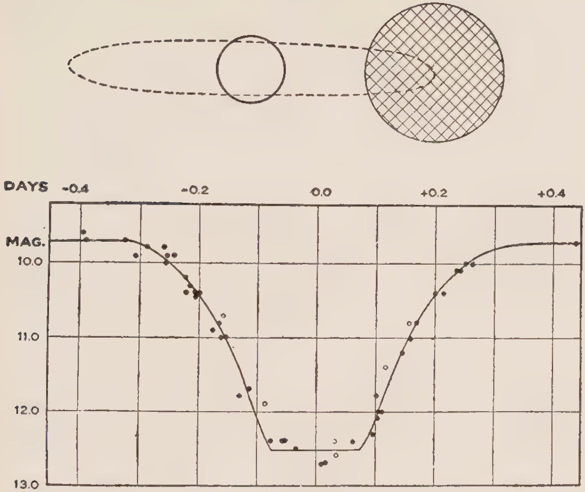


FIGURE 1. Light curve of eclipsing variable at and near the principal minimum, the points representing individual observations of magnitude. A diagram of the computed orbit of the large companion relative to its much brighter primary is given below.

dicating that the components have the same surface brightness.

Eclipsing Binary Stars

Figure 1 gives a graphical representation of the light variations for a typical eclipsing double, composed of a small bright star and a larger companion. The curve shows that between eclipses, when the two stars are clear of each other, the light remains constant; but as one star begins to conceal the other, the

light diminshes gradually until minimum brightness is attained, the smaller star then being completely concealed by the larger. The maximum light slowly returns as the small star emerges.

The determination of the light curves of eclipsing variable stars is an active branch of astronomy at the present time. In recent years, moreover, the mathematical analysis of the curves has revealed the physical nature of these variables and led to knowledge of the actual dimensions of stars. The theoretical and computational work has been done largely at the Princeton Observatory by Russell, Dugan, and Shapley. More than a hundred orbits have been solved. For each system the interval of time between eclipses and the shape of the light curve can lead to knowledge not only of the elongation of the components (they are frequently not spherical), but also of their sizes in terms of their distance apart, the relative brightness of their surfaces, their specific gravity, the shape of their orbits, and other properties.

Detailed discussion of these interesting double stars would be too technical for the present essay, but their importance in the problem of the dimensions of stars may be readily indicated. The study of the light curves gives the diameters of the components of a pair in terms of the distance separating their centers. If we know also how big the

orbit is in linear measurement, we can express all diameters in miles. For the solution of this problem of orbital dimensions we appeal again to the spectroscope.

The Doppler shifts, described in the last chapter, are known for some eclipsing binaries. The shift of the absorption lines can readily be translated into miles per second of approach or recession—that is, into the velocity of the stars in their orbits. We know from the interval of time between eclipses how long it takes the star to make a complete revolution, and knowing the speed we readily compute the size of the orbit. With orbits measured, we compute the dimensions of the stars themselves from the data yielded by analysis of the eclipses.

The Interferometer

The direct measurement of the angular and linear diameters of stars, as we measure the diameter of a planet, is of course impossible because of the greater distances. In recent years, however, an accessory optical instrument, the Michelson interferometer, has been used in connection with the 100-inch telescope at Mount Wilson to measure by somewhat indirect methods the angular diameters of some of the largest stars. When the distances of these stars are known, the angular measures can be turned into linear measures, and expressed in miles or in terms of the sun's dia-

meter. The measures with the interferometer confirm the results found from eclipsing stars, and also agree with theoretical considerations that had permitted the deduction of the probable diameter of a star from knowledge of its absolute brightness and color.

As is now well known, the work with the eclipsing stars and with the stellar interferometer reveals the existence of gigantic stars, the diameters of some of which even exceed the diameter of the earth's orbit. Betelgeux and Antares are among the giants measured at Mount Wilson. Apparently many red giants have diameters in excess of 300,000,000 miles, and volumes, therefore, more than thirty million times that of the sun.

Among the eclipsing stars, dwarf systems have also been found—pairs of stars each of which is no larger than the sun. In figure 2 the orbits of two eclipsing variable, W Crucis, a giant, and U Pegasi, a dwarf, are shown diagramatically; but the linear dimensions of the giant pair had to be reduced to one-fourth to bring it conveniently within the diagram. The sun is drawn to the scale of the dwarf stars.

The sun is obviously small compared with the reddish giants, but it measures up well with the average dwarf. Dwarfs and giants frequently have the same spectra, and therefore the same colors and surface tempera-

tures. This matter will be of high importance in our later consideration of stellar evolution.

Stellar Masses

The masses of stars are not as yet well known. We have no good quantitative method of getting at the masses of any single star except the sun. For a number of binary stars,

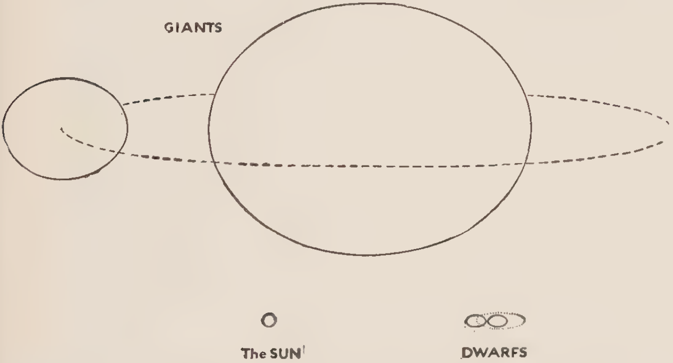


FIGURE 2. Relative dimensions of the sun, the dwarf binary U Pegasi, and the giant binary W Crucis. (The last has been reduced to one-fourth.) The spectra and temperatures of all these stars are much alike.

however, the masses are found by studies of the orbits and distances. The more massive a star, the shorter its period of revolution for an orbit of given size.

In so far as they have been determined, however, no great differences in mass are found. The range is between one-fifth the mass of the

sun, and ten times the mass of the sun, except for a few special cases. The range in volumes is much greater than the range in mass. This means that the big volumes are associated with low density rather than with large material content. Giant stars are puffed out with gas of great rarity; they are giants in girth, but not in stuff.

Among the exceptionally large masses are those eclipsing binaries in which the two components move about each other with a relative velocity of several hundred miles a second. The most massive system yet known is one discovered and measured by Plaskett at the Astrophysical Observatory of the Dominion of Canada. The two stars together are equal to at least 150 suns in mass. A few Class B doubles have about thirty times the sun's mass; many stars of spectral classes A and B are from three to ten times as massive as the sun. But taking the stars as a whole, giants and dwarfs, the sun appears to be somewhere near the average. The same is probably true of its size, as well, for the great majority of stars are dwarfs.

Part II

THE EVOLUTION OF STARS AND PLANETS

VI

THE NEBULOUS PARENTAGE OF STARS

THE word nebulous might be used in two different senses in the title of this chapter, referring either to intellectual or to material conditions. We know something, it is true, of the evolution of stars—once they are born; but our knowledge of their birth is very nebulous and hazy. As far as it goes, however, the information at hand favors the various hypotheses that associate the genesis of stars with celestial nebulosity.

In the preceding five chapters an effort has been made to give the reader a general idea of the nature of stars and planets. In the first two chapters we saw that there are many kinds among the sun's neighbors—stars of different colors, of various sizes, of diverse speeds and associations. There are also a few nebulae visible with the unaided eye, especially the great spiral in Andromeda, and the large, irregular, and diffuse nebula in Orion's sword.

But most stars and nebulae are telescopic, widely scattered throughout a disk-shaped system, the galaxy. In the Milky Way (described in Chapter III), the stars are so numerous that a single photograph may register more than half a million at a time. Among these galactic objects there are many classes, as described in the fourth chapter, and the obvious relation of one type to another leads us to believe immediately that we see therein traces of stellar evolution. Finally, in considering the sizes of stars, we find that some are enormously large and luminous and of low density, while others are of low candle-power, high density, and as small as the sun in diameter, or even smaller. One of the major problems of astronomy is to decide whether and in what manner a dwarf star can change into a giant, a red star into a blue star, a rare star into a dense star, a single star into a double, or vice versa in each of these cases. If we can answer these questions, we have begun the solution of stellar evolution; and in solving completely the evolution of stars we also answer the questions of the earth's origin, and the questions of the inorganic development on the earth which was a necessary antecedent of terrestrial life.

The Theory of Kant

Immanuel Kant was one of the first great and successful thinkers on the problem of

stellar evolution. Basing his conjectures on Newton's laws of motion, he announced a theory that may in part be summarized briefly as follows:

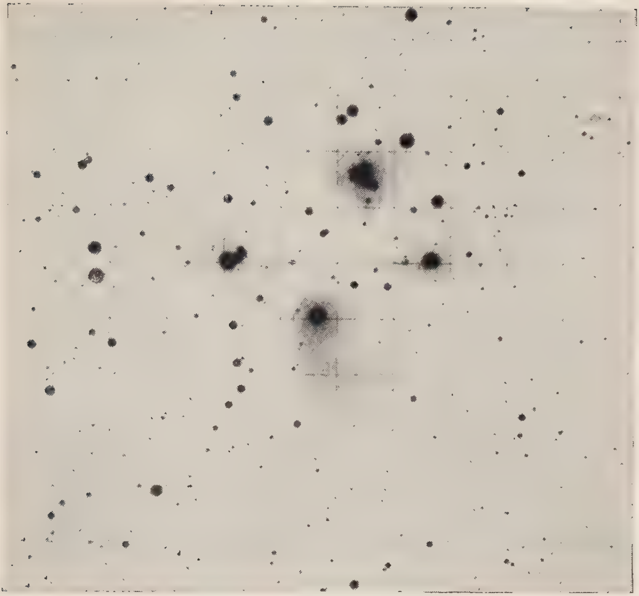
Originally the universe was filled with disorganized matter at rest. (He left unsolved the question of the origin of that matter.) Under the action of gravitation, this material began to fall together, forming nuclei in the great original nebulosity. The growing nuclei eventually became suns at the centers of systems, attracting the original disorganized matter and smaller nuclei into their gravitational domains. In some manner, through the interaction of the falling particles, a rotational motion was set up. Secondary nuclei became the embryos of planets. Endowed with a transverse motion, these primitive planets fell around the glowing central suns, and not into them.

Thus Kant visualized the origin of a central sun, surrounded by a group of planets, some of which, in a similar manner, collected satellites. He believed that in a comparable way the other stars developed, and that the Milky Way system is an enormous "world of worlds." He suggested also, as mentioned on an earlier page, that the spiral nebulae might be other galactic systems, composed of myriads of stars, and each star possibly surrounded by planets and their satellites.

The Theory of Laplace

In many ways Kant's speculations, based on a small amount of observational material, were exceptionally good. His views of the origin of suns and planets remained little known, however; and independently, about forty years later, the great French mathematician Laplace proposed a somewhat similar Nebular Hypothesis. Laplace considered the nature of the solar system only (not of the stars or galaxy). He believed, as did Kant, that contraction from a nebula was the source of the sun. He believed, however, that from the beginning the sun was a hot, greatly extended, rotating body, and that in the course of its gravitational shrinkage it cast off rings of matter. Each ring, he believed, would be ultimately transformed into a planet, all the material of a ring, or at least a large part of it, being absorbed into one body—a planet body that at first was hot, but later cooled and, for the smaller planets like the earth, became crusted on the surface.

Laplace's hypothesis, although not vigorously espoused by its author, became the standard theory for a century. In Chapter X we shall see why neither the theory of Laplace nor that of Kant is maintained at the present time to account for the origin of the planets. But the theory is held to the present day that, through gravitational contraction, the stars have condensed out of nebulae,



The Pleiades with irregular nebulosity surrounding the brighter stars. The field is marked off in square degrees.

and that one of the sources of their radiant energy is the falling together of their material.

There are two reasons why scientists associate disorganized nebulosity with the evolution of stars. One is the theoretical reason that large masses of cool gas or dust would inevitably condense into spherical bodies, become hot through progressive contraction, radiate energy away, and continue contracting and radiating in accordance with the well known laws of gases. The second reason is that nebulosity and stars are frequently observed closely associated in sidereal space.

A diffuse nebulosity, for example, surrounds the Pleiades. Many of the naked-eye stars in Orion are immediately associated with outlying parts of the great Orion nebula. The fact that, in these and similar cases, the stars most closely connected with the nebulosity are the bluest and hottest of all types, led many years ago to the assumption, now considered erroneous, that when a star first developed out of nebulosity it is at maximum temperature; its further evolution being a progression down the temperature scale, from Classes O and B through Classes A, F, G, K, to M and the other redder types.

The association of hot stars with luminous nebulosity is now explained in another way. The mixture of dust and gases in the diffuse nebulae (shown in the accompanying photo-

graph of the Pleiades) is visible because of the excessive radiation bombarding it from the bluish hot stars involved. There may be similar nebulosity around the redder stars, but the intensity of their radiations is not sufficient to excite the material to luminescence. Thus the *visible* nebula associated with stars is believed to be the product of the stars rather than the parent.

Bright and Dark Nebulae

In speaking of the luminous nebulosity we have plainly intimated that many nebulae are dark. The extensive photographic work of Barnard, Wolf, Bailey, Hubble, and others with powerful photographic telescopes, has shown the common occurrence of lightless nebulae. Large regions of the sky are affected by these obscure cosmic clouds, which become known photographically because they shut off from our sight the fields of more distant stars. They are detected by deficiencies and irregularities in stellar distribution.

It is this dark nebulosity, which usually is partly luminous only if in the vicinity of bright hot stars, that is believed by many astronomers to be directly involved in stellar ancestry. In the next chapter the best authenticated of the interpretations of stellar evolution will be presented briefly, emphasizing not only the conspicuous advance it represents but also its lack of finality.

VII

THE CURRENT THEORY OF STELLAR EVOLUTION

THE impressive circumstance that practically every star can be arranged in a continuous temperature series has guided all recent considerations of stellar evolution. The temperatures are found, as previously explained, from the distribution of light throughout the spectra. The temperature sequence, running from the bluish stars of Classes O, B, and A, down to the reddish stars of Classes M, N, R, and S, presents a continuous gradation throughout, from 50,000° F to 5,000° F, and less. There are, associated with this gradation, almost imperceptible steps in color, spectrum, distribution in the sky, and other characteristics. We do not see directly the progress and processes of the evolution of any star, except perhaps sporadic catastrophes, but after a glance at the various orderly sequences we cannot escape the conclusion that individ-

ual stars pass along the spectral series, evolving according to natural laws from one class to another.

The "Two-Branch" Theory

Sir Norman Lockyer was the first to emphasize, and support with observations of a crucial sort, the hypothesis that in its life history of contraction from the most primitive state, a star would first warm up from obscurity, become visible, increase in temperature to some maximum stage, and then fall off in brightness and surface intensity, approaching redness, old age, and extinction. He thus pictured two branches to the evolutionary series—a star going twice through the sequence of spectral classes, once on the rising scale of temperature, during its youth, and again on the descending scale in later life.

Lockyer's theory was not generally accepted by scientists for reasons that cannot be discussed here. He advocated, perhaps overstrongly, the view that swarms of meteors composed the stars, and that meteors could be used to explain nearly all past and present cosmic phenomena. His hypothesis, called the meteoric theory, brings forward, in more concrete form, some of the vague ideas of Kant concerning the origin of stars. Lockyer supported his speculations on stellar evolution with a rich amount of spectroscopic material; he was, indeed, ahead of his time in

astrophysical thinking and in hypotheses concerning the structure and behavior of matter at the high temperatures prevailing in stellar atmospheres.

Some twelve years ago Professor H. N. Russell, of Princeton, began to study vigorously and to advocate the "two-branch" evolutionary scheme. He pointed out, with much greater certainty than Lockyer could command thirty years before, that the natural development of star from nebula, according to what we know of the behavior of gases, should be a series of rising temperature stages from spectral class M toward A and B, followed by a series of dwarf stages, running in the reverse order through the classes in the direction B, A, F, G, K, and M. Russell showed that this procedure was theoretically reasonable, and he also brought to its support much observational material from many fields of astronomy. Especially the existence of giants and dwarfs among the red stars was taken to indicate early and late stages in the life history of typical stellar masses. Betelgeux, for instance, is young; Sirius is middle aged, and the sun has long since passed its prime of brightness and slowly approaches senility.

Others have contributed to the Lockyer-Russell hypothesis during the last years. In particular, Professor Eddington has made important mathematical investigations of radiating masses of gas. His work has recently indi-

cated the possibility of stellar material that obeys the laws of gases, though more than four thousand times as dense as lead; and Adams' observations on the faint companion of Sirius appear to verify the existence of such abnormal gaseous objects.

The Russell theory easily holds the field at the present time, since it succeeds in co-ordinating and explaining most of the ordinary observations on stars and nebulae. But we should record also that various difficulties are recognized. Undoubtedly the hypothesis must be modified in some details. For instance, the stage of evolution that antecedes the presumably youngest giant star as yet remains obscure. No pre-giants have been recognized. Also the source of energy that supports the radiation during the evolution of stars is still unknown. Gravitational contraction will supply an enormous amount of energy for radiation into space, but modern researches on the extreme slowness with which evolution proceeds, indicate that this contractional source is far from sufficient.

The Source of Energy

Let us digress here a little to note that the perplexing question of the source of stellar energy is all mixed up with the problem of the structure and behavior of atoms under conditions of high temperature and pressure. As usual, the answer must await more observa-

tion. If the energy for the radiation of the sun, for example, were derived solely from its contraction, the whole supply in the past would have lasted not more than ten or twenty million years, at the present rate of emission. This time is far too little. We now know that most of the fossil-bearing rocks of the earth are much older than twenty million years. The character of the fossils indicates, moreover, that solar radiation is much the same now as some hundreds of millions of years ago.

Obviously then we must look to some source of energy for solar radiation other than gravitation. The problem has been investigated by many scientists in the fields of geology, physics, and astronomy. Ordinary radio-activity in the sun would provide insufficiently; chemical and electrical sources would help too little. The general feeling at present is that the only sufficient source available lies in sub-atomic energy. The amount of energy in the atoms of matter is enormously great, and a simple computation shows that if one per cent of the sun's mass had been transformed into available energy in the past, it would have sufficed to supply radiation throughout the whole history of the earth's crust.

The simplest way, theoretically speaking, of releasing the internal energy of the atoms is in the transmutation of the elements, especially in the building up of hydrogen atoms

into elements more complex. Hydrogen is now believed to be the basic building block for the formation of all the heavier chemical elements, and the comparison of its mass, when isolated, with the resulting masses when built up into helium, oxygen, and other elements, shows that nearly one per cent has disappeared in the process. Presumably the mass that is lost, in the supposed synthesis of higher elements out of hydrogen, is transformed into radiant energy. The loss to mass is a gain to energy for radiation. Atom building may run the stars.

Although we cannot ourselves trim the small fraction of energy from an atom of hydrogen, it appears that the stars can accomplish this feat. We have, therefore, as a product of our study of stellar evolution, a strong indication that sub-atomic energy is released under special physical conditions. Perhaps some day we shall learn the secret of the stars and thus solve man's present struggle for power.

The Age of Stars

There are three observational reasons for believing that the evolution of stars is so slow that energy released by gravitational contraction is insufficient to account for stellar radiation. First, the age of terrestrial rocks has been found to exceed a thousand million years. Second, the giant stars differing in age by two hundred thousand years show no measur-

able evidence of development, while on the contractional basis the whole giant-stage life of such stars should be put at a few thousand years. Third, certain giant variable stars, called the Cepheids, of which Polaris is one, show very small or no changes in period as time goes by, although they have been under observation for scores of years; on the contraction theory, the internal density of the Cepheids should increase sufficiently in a few years to modify conspicuously this period of variability. Apparently the radiation is maintained in other ways; probably the stars keep expanded with the heat from the sub-atomic sources, and the contraction and evolution proceed at an immeasurably slow rate.

If the speed of development depends only on the rate at which a star loses its mass through radiation, then the past life of a star like the sun has probably been several million million years. And on the same basis its luminous future would not be less extensive, though its brilliancy would continually grow less.

The theory described in this chapter accounts for star life, but not for planets and organic phenomena, and other small things in the sidereal universe. We shall now approach planetary origins through two preparatory chapters that deal with space, time, meteors, and celestial catastrophes.

VIII

CONCERNING THE EMPTINESS OF SPACE

A WATCHER of the skies on any clear moonless night can see several meteors or shooting stars as the reward of a few hours observing. By watching attentively, he will find that the meteors are more numerous after midnight than before, and that on some nights of the year they are more frequent than on others. Since the meteors are phenomena of the earth's upper atmosphere—the combustion through friction of small particles that rush in at high speed—they are indicators of the loose material in the space that surrounds and pervades the solar system. They show that interplanetary space is not completely empty.

Importance of Meteors

It has been reliably estimated that the number of meteors striking the earth's atmosphere is more than ten millions a day. At first

thought this enormous number appears to indicate that the earth is rapidly growing in mass and that space must contain great quantities of meteoric material. Recent investigations, however, have confirmed the earlier belief that the meteors are of minute mass. Their diameters possibly average less than a millimeter; they are scarcely more than grains of dust. The bright flashes that commonly occur in the hurried dissolution in the earth's air, are to be attributed to great speed—about twenty-five miles a second on the average.

Not all of the meteoric bodies that the earth meets are of small dimensions, however, for occasionally one that is composed of iron or stone, or a mixture of materials, penetrates the protecting atmosphere and strikes the surface of the earth. These so-called meteorites may be the remnants of the nuclei of comets' heads; for certainly many of the smaller, dust-like meteors are the detritus of dissolving comets. Or possibly the meteorites may be the ejecta from lunar volcanoes—cast forth when the mountains of the moon were active in the remote past; or perhaps they are the debris remaining from the earlier stages of the planetary system; or they may be wandering fragments from interstellar space, not heretofore associated with the solar system. The chemistry of meteorites is carefully studied with each new discovery, but as yet no element unknown to the earth's surface has been

found, and no novelty appears in the materials sufficient to indicate origin in a remote part of space where the chemistry and mineralogy might be peculiar.

Presumably meteors and meteorites are scattered throughout the whole solar system, but are more frequent near the sun. The zodiacal light, often seen distinctly as a luminous band extending up from the western horizon after sunset, or from the eastern horizon before sunrise, is generally explained as the reflection of sunlight from the swarms of meteoric particles between the earth and sun.

Each particle, whether a dust grain or an iron mass of many tons, follows its own orbit around the sun, except when disturbed by the attraction of a passing planet, or when captured in a planetary atmosphere. Long ago the meteorites may have been larger and more numerous. One theory attempts to explain the craters of the moon as marks left by great meteors falling in at a time in the past when the lunar surface was partially or completely molten. But the alternative theory, that ancient volcanic eruptions and bubbling caused lunar craters, has more adherents at the present time.

From the alternative and equivocal statements in the foregoing paragraphs, it is obvious that much remains unknown in meteoric astronomy. There is hope, however, for advancement in the near future through special

studies. The National Academy of Sciences has recently provided a limited fund to the Harvard Observatory to aid the study by an expert of the hundreds of meteor trails on record in the Harvard library of stellar photographs. Already important results on the nature of meteors are coming to hand. In addition to large numbers of typical shooting stars, rotating meteors have been photographed, also double meteors, meteoric spectra, meteors that travel curved paths, and other curiosities—all of which throw light on the constitution of these minute wanderers in space that seem to be so fundamental in the origin, growth, and decay of stars and planets. This research on meteors illustrates the possibilities of investigation with the extensive Harvard collection of plates, when means are provided to support the work.

Comets and Asteroids

Aside from the known planets, moons, and asteroids, these numerous meteors and the comets are the only known inhabitants of the solar system. The comets, of which three or four are seen each year, travelling in elongated paths around the sun, are now believed all to be members of the sun's family. They may be remnants of the original solar nebula.

In recent years some objects have been found which may be classed either as tail-less comets whose orbits are much less elongated

than ordinary, or as asteroids with orbits of unusually large eccentricity. The average asteroid (there are a thousand now known) is a body of 10 to 50 miles diameter revolving around the sun in an orbit, of fairly small eccentricity, which lies between the orbits of Mars and Jupiter. Some comets and asteroids appear to be of comparable dimensions, and their periods of revolution around the sun are much the same. It will be interesting to see if future discoveries will show a complete graded series from the average asteroid to the average comet, thus connecting these minor parts of the solar family, much as meteors and comets have already been associated.

Population of Solar Domain

Notwithstanding the large numbers of minor bodies in the space around the earth, astronomers are convinced that interstellar regions are sparsely populated. The distance separating luminous stars is incomparably great compared with the diameters of the stars themselves, or compared with the diameters of their planetary systems. The solar domain, defined as the spherical volume of space with a radius one-half the distance to the nearest star, is a volume of about forty cubic light years, and 100,000,000,000 times the volume of space covered by the solar family. Yet within that extensive domain, we know of no material except that which is thinly scattered in the plane-

tary system. The rest may be void of matter, or it may be occupied by non-luminous material in the form of gas, dust, or larger sidereal bodies.

We know nothing of the existence or non-existence of lightless stars, except, possibly, in one respect. If there were large numbers of dark bodies in space, their gravitative effect on other stars could be discerned through measures of motions. The observed velocities of stellar bodies are, however, of the magnitude to be expected if there were very few or no masses besides those of known luminous stars. This test of the absence of free wandering planets, or of extinct suns, is, it should be admitted, not very sensitive.

Space and Light

Another recent investigation throws some light on the emptiness of space, but it also does not prove *conclusively* that space may not have much obscure material of a stellar or meteoritic nature. When the light from a star passes through the earth's atmosphere a portion is scattered by the gaseous materials of the air and by the floating dust. Some light is reflected back into space from clouds and from the various layers of the atmosphere. The light from the setting or rising sun necessarily passes through the greatest thickness of the air, and its characteristic yellowish and reddish color arises from the fact that blue light

is more readily scattered and lost than the longer wave-lengths of red and orange light. The light from a star is similarly scattered and reddened, and proportionately more when the star is near the horizon.

If there were sufficient gaseous and dusty material throughout space, star light would be affected there as in our atmosphere, and the more distant stars would suffer the greatest loss. Hence, we have here a means of testing for the scattering effect in space: is the light of distant stars redder than that of near-by stars?

The earlier work on the problem of spatial light-scattering, some ten to twenty years ago, seemed to show an effect on star colors, indicating much material in space; but subsequent investigations by the writer have shown that the space-effect on starlight is quite inappreciable. It has been possible to measure photographically the color of stars that are one hundred times as distant as those used in all earlier work, and these distant objects when carefully studied were found to be just as blue as stars of similar spectral class in the solar neighborhood.* It was found, in fact, that pulses of light can travel through interstellar space for two thousand centuries, at the speed

* The reddening effect of the earth's atmosphere is, of course, the same for all stars, independently of distance, provided their angular positions above the horizon are the same when comparisons are made.

of 11,000,000 miles a minute, without encountering as much light-scattering material as they meet in a thousandth of a second as they pass through the earth's lower atmosphere.

I have also made another test that bears on the emptiness of space, and the freedom of light pulses or waves from disturbance in their passage to the earth from distant celestial bodies. Periodic variable stars of the Cepheid type, referred to in the next chapter and in Chapter XII, are found in very distant star clusters. It is possible to measure accurately the time at which a variable of this kind attains its maximum brightness. The time can be determined with the aid of measures on photographs made in rapid succession. When some of the photographic plates are sensitive only to blue light and others only to yellow, we can find the time of maximum in the light of two different colors (wave-lengths).

Now, if the velocity of light were not the same for different wave-lengths, or if the material in space (or space itself), or the time of passage, affected the velocity of light differently for different colors, the photographs should reveal the discrepancies. They would show the blue maximum later or earlier than the yellow maximum. The results for many variables in a remote cluster show, however, the same velocity for the two colors within the errors of measurement. The speeds do not

differ by more than one part in twenty thousand million, if at all.

The Isolation of Earth and Sun

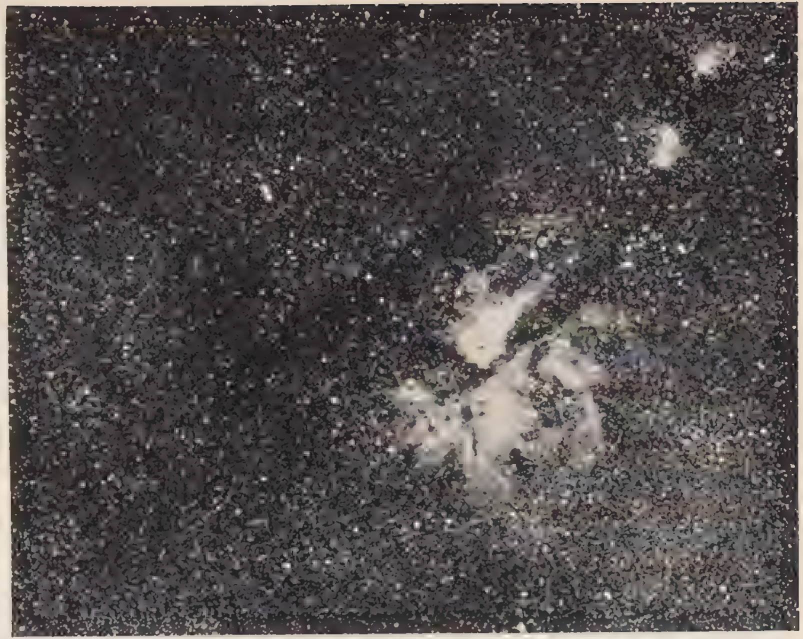
The various observations described above emphasize how greatly the stars are isolated, and, in the sun's vicinity, how much greater is the unpopulated space than that occupied by known sun and planets. Even the relatively small volume of empty space within the orbit of Neptune is almost inexpressibly larger than the volume actually occupied by the sun and all its planets; it is, in fact, two hundred thousand million times larger; and the sun's volume is a million times that of the earth. In such a pronounced emptiness it is not surprising that the sun and earth can travel for centuries, or even milleniums, without serious disturbance.

In the next chapter we shall consider the volumes of some of the nebulae and the likelihood of collisions and close approaches between sidereal bodies. The possibility of near encounters will appear as a highly interesting factor in the evolution of planetary systems.

IX

CELESTIAL COLLISIONS AND ENCOUNTERS

THE distance of the Orion Nebula is approximately six hundred light years. The diameter of the portion of the nebula that can be seen with a small telescope is about five light years. The nebula, however, is much larger than it appears visually. Long exposure photographs with appropriate telescopes show that around the luminous part is a large obscure region, some of which is here and there dimly illuminated. In fact, throughout the whole constellation of Orion is bright and dark nebulosity, and surrounding the central visible nebula is a region, with a diameter of at least fifty light years, that is so densely nebulous that stars behind are hidden. Here, then, is a large part of space that is not nearly as empty as the solar domain. The encounter of a star with such a nebula is quite a different problem from the impact of star on star.



The irregular gaseous nebula surrounding Eta Carinae in the southernmost part of the Milky Way. Photographed at the Harvard Observatory station in Peru.

At its present rate of travel through space, the solar system would require 65,000 years to cover the distance to the nearest star. The frequency of stars throughout the galactic system is little if any greater than in the solar neighborhood. Collisions between stars must, therefore, be exceedingly infrequent. But the probability of collision between a star and a great diffuse nebula is much higher.

Variable Stars in Orion

Investigations of the last ten years have shown conclusively that most of the bright stars in Orion form a large moving cluster. Many of the stars of the cluster are within the limits of the bright nebulosity that makes up the visible Orion nebula. Since there is no rest in the universe—all stars and nebulae being in motion with respect to each other—there must be frequent encounters of star and nebulosity in the Orion region. What is the result of these encounters on the stars, and on whatever planets they may have?

There can be little doubt that, if two stars moving with a relative velocity of twenty or thirty miles a second should collide, the consequence would be discernible at great distances. Nebulosity is of great rarity, however; it is often compared to the highest vacuum yet attained in our physical laboratories. Hence, we could not predict offhand the effect of a stellar-nebular collision. If, how-

ever, we turn to the Orion nebula and the cluster of bright and telescopic stars associated with it, we find an interesting phenomenon that appears to bear directly on the question.

Within three degrees of the Trapezium, which is the group of high temperature stars collectively designated as θ Orionis and which is the center and probably the radiant source of the brightest part of the nebula, there are more than a hundred faint stars that measurably vary in brightness. A consideration of these stars is of importance for the light they throw on stellar variability in general as well as for their bearing on the problem of sidereal evolution.

The faint Orion variables were mainly discovered on photographs made at Harvard, though some were found elsewhere, especially at Heidelberg by Professor Max Wolf. They are, on the average, of the fifteenth magnitude—considerably fainter than most known variable stars, except some of those in clusters and in the Magellanic Clouds. From the available fragmentary studies of their proper motions and their distribution with respect to the nebula, it seems that these faint variables are actually members of the Orion cluster, and are not, as sometimes suggested, stars much more distant than the nebula. If this conclusion is correct, we have in the faint variables in Orion a feature never before met in groups of variable stars. Practically all other known

variables are giants, but these in Orion must be dwarfs in luminosity, since they are of the fifteenth apparent magnitude at a distance of only six hundred light years. They must be, indeed, intrinsically as faint as the sun and many of them much fainter.

What sort of variables are these dwarfs in Orion? Are they eclipsing stars, such as Algol and Spica; or Cepheids, like Polaris and the numerous variables in the globular clusters and the Magellanic Clouds; or are they long period variables, such as Mira, which varies several magnitudes in brightness in a period of about a year? The Harvard observers naturally expected that upon thorough study the Orion nebula variables would prove to be Cepheids. In other congested regions, like the clusters, practically every variable periodically rises rapidly to a maximum and slowly decreases, in the manner characteristic of the Cepheids. But the preliminary observations of the Orion variables failed to reveal periodicity. No law for the variations could be found. The fluctuations were irregular and unpredictable, and at times very pronounced.

Several observatories took up the problem of the Orion variables, all working photographically; but still the rules underlying the variability of these stars were not deciphered. Among others, the present writer, then working with the large reflecting telescopes at Mount Wilson, took large numbers of photo-

graphs of the faint Orion variables and systematically measured the photographic images, finally proposing that we have here a new type of variable and that the variation in brightness arises from the relative movement of stars and nebulosity.

An alternative explanation of these variables is that they are not dwarfs, but, lying far beyond the nebula, are ordinary or giant stars whose variations in light are attributable to eclipses by the moving nebulous material between them and the earth. The objections that may be raised against this interpretation are of considerable weight but they cannot be taken up in this essay.

Apparently, one of the results of the encounter of star and diffuse nebulosity is to incite irregular variability in the star's light. Recently other variables of this sort have been found in other regions filled with nebulous material. The type may be common near diffuse nebulae.

Collision of Star and Nebula

We can only conjecture what might happen on the earth and sun, if the solar system moved into such a nebulous region. The variability of past climates on the earth, as revealed by the geological records, may be in some part due to the nebulous fields through which the sun and planets have moved. Since the time when Precambrian rocks were formed, the sun

has probably covered a path equal to sixty times the distance to the Orion nebula. There is little chance that through all its travels, it has completely avoided the widely spread nebulous regions, though it may have escaped the denser and too disturbing centers of nebulosity, for no really catastrophic variability of the sun has occured in geological time. But it seems probable that, during past geological ages the cosmic dust and gases, which are exampled in the meteors and the diffuse nebulae, may have contributed to changes in terrestrial temperatures and therefore to the progress and regress of the evolution of terrestrial life.

Another more spectacular and astronomically more significant result of the encounter of star and nebula is associated with the phenomena of novae or new stars. Two or three times a year, on the average, astronomers record the temporary appearance of a star where none was previously known, or, if known, was exceedingly faint. There are several historical cases in which, apparently from nothing, a star has appeared suddenly of the first magnitude.

The remarkable changes in the spectrum of such a star at maximum brightness and during its slow return to obscurity have been studied in particular at the Yerkes, Mount Wilson, and Lick Observatories. The peculiar changes in the brightness of novae on the ris-

ing and descending branches of their light curves have been especially studied at the Harvard Observatory, with the aid of thousands of photographs. Occasionally a nova, after quieting down, suddenly reappears; but generally a single flashing-up and irregular fading away to the original magnitude, followed eventually by slight irregular variability throughout several years, constitute the photometric history.

The rise of a nova to maximum (with a few exceptions) is phenomenal in its speed and occasionally in its extent. A change of fifteen magnitudes has apparently occurred in twenty-four hours, corresponding to an increase of a million times in light emission.

Theories of "New Stars"

An examination of the light curves derived at Harvard shows that some novae are intermediate in character between the typical novae and irregular variables. This circumstance, of course, suggests that the source of disturbance may be the same for novae and for variables of the Orion Nebula type. In fact many years ago Monck and Seeliger supposed that novae may be the result of collision between star and nebula.

Other theories of novae have been introduced, such as the falling of a planet into its sun, the explosion of a star, the collision of two stars, and the collision of two meteor

streams. Concerning the latter we really know too little to maintain or criticize. With regard to stars colliding to produce a nova, the spectroscopic evidence opposes, as also does the circumstance that novae occur frequently while statistical computations show that in our whole stellar system two stars cannot be expected to collide oftener than once in ten million million years. The hypotheses of explosions incited by a planet falling into a sun or by the collision of a star with some great comet of its system have some points in their favor; but they are exceedingly indefinite—for instance, we do not actually know of the existence of any comets or planets around other stars.

The explosion theories of novae can be better considered when we know more of the interior of a star, and of its mode of formation. In general, however, the hypotheses of collision and explosion must be closely associated, for the latter would likely result from the former. The star is in a stable, but undoubtedly sensitive equilibrium between its centripetal force of gravitation, and its centrifugal forces arising from rotation, gas pressure, and especially radiation. When some change in the external physical environment arises, affecting too suddenly the balance between radiation and gravitation, an upset of equilibrium may be expected. The sudden change in balance may

easily result in nova-like catastrophe for a star in a critical condition.

It appears, therefore, that a star plunging into a nebula may react either as a typical irregular variable or as a more catastrophic nova, depending on the relative speeds, and especially on the composition and density of the star and nebula. If the result is of the nova character, the enormous changes in brightness and the evidences of abnormal velocities in the expanding atmosphere arise, no doubt, from explosive action from within incited by the disturbance from without.

Frequency of Novae

The importance of calling attention in some detail to these novae and to the so-called "collision variable stars" lies not only in the possibility of the sun's association with the cosmic clouds, in the past or future, but more especially in the probable bearing on stellar evolution. If two or three new stars are recorded each year, the total number throughout even a short astronomical interval of time becomes collossal. At such a rate, there have been thousands of millions of "new stars," since the earth was born, even allowing for the fact that occasionally a nova repeats itself.

Probably most stars that undergo the nova disaster are previously typical and after an interval of ten or twenty years return to their original condition; but some are known to be

very peculiar in spectrum for scores of years after the outburst. Still others, which have originally been very massive or have undergone exceptionally violent reactions, may be the antecedents of one type of gaseous nebula.

In concluding this discussion of stellar collisions, three further statements may be made summarily. The application to the foregoing remarks will be clear.

(1) The novae are confined to the Milky Way, and are often in regions known to be nebulous.

(2) Some of the faint Orion variables have been recorded as nova-like—that is, the light has risen to a single sudden maximum and then has slowly died away; but in no cases in the Orion nebula are the ranges more than two or three magnitudes, therein differing from the typical novae, with their ranges of five or six magnitudes and more.

(3) In certain spiral nebulae, especially the great nebula in Andromeda, many novae have been found in recent years. The spiral nebulae as a class have higher velocities than any other class of celestial bodies. The Andromeda nebula, for instance, is approaching the sun at the speed of two hundred miles a second.

Much of our stock of information on novae, as well as on stellar constitution and evolution, is the product of the activity of the present century. We have learned more concerning

the physical conditions of the stars during the last twenty years than has been accumulated in all preceding time. It would be expecting too much, therefore, to hope that our present interpretation of the vast amount of new material is correct and final. Because of this caution, many alternative hypotheses have been mentioned in the preceding pages, though frequently they are little believed.

X

THE EARTH'S ORIGIN

LET us now consider what effect the collision or encounter with a star might have upon our sun. It appears that the encounter with nebulosity might alter the brightness of sunlight, in some irregular manner, by forty percent or more, if we have correctly interpreted the phenomena observed for variables in the Orion nebula and similar regions. We cannot in like manner observe directly the effect of an encounter between stars, but we can imagine the course of events. This has already been done by various astronomers seeking an explanation of novae, and by Chamberlin and Moulton, Jeffreys and Jeans in their consideration of the origin of planetary systems.

Before taking up the possibility that a stellar collision is at the root of planetary origin, Jeans studied mathematically the forms of rotating gaseous bodies and considered the applicability of Laplace's Nebular Hypothesis.

He found in brief that, if a sidereal mass is large enough, the inevitable increase of rotational speed, as contraction proceeds under the force of gravity, will result finally in the ejection of matter from the equator of the rotating body. The spiral nebulae, he believes, are such products of the evolution of great masses in rotation.

The Birth of Double Stars

For a mass of stellar size, however, the rotation will first flatten the gaseous body at the poles, much as the earth is flattened through its rotation, and then, with the increase of rotation, transform the spheroidal star into an ellipsoidal body. A still greater increase in rotational velocity, as the star further contracts under the gravitational infall of its parts, may result in fission—the ellipsoidal body may break in two and form a close double star, of the sort we have already considered in Chapter V.

Jeans' theory, which carries forward the work of Poincaré, Darwin, and others, is now widely accepted as explaining satisfactorily the genesis of close double stars. The hypothesis can readily be supported from the observation of eclipsing stars and other doubles, since pairs of ellipsoidal stars, with surfaces nearly touching, are frequent, and there is also pretty good evidence that a few much-elongated single stars are on record. But the rotating gaseous

body does not appear to be a direct forerunner of the planetary system, which is the main object of our immediate inquiry.

Disruptive Encounters

On the other hand, the tidal evolution theory of the origin of planets, which is but a modification in certain details of the Chamberlin-Moulton planetesimal hypothesis*, appears to afford a very satisfactory explanation of the phenomena observed in the planetary system. And this tidal evolution theory involves stellar encounters.

Perhaps, then, our question concerning the outcome of collisions is answered: the encounter of a star with nebulosity produces a variable star, or a nova, or possibly even in extreme cases a bright nebula; an encounter with another star, if not too disruptive, may result in a creative disaster such as that which produced the earth and the sun's other planets. Sudden disruption rather than rotational fission appears to have generated the present solar system.

The Nebular Hypothesis

It will be of interest to examine the scientific theories of the earth's origin historically. Nothing that can claim a definite and detailed scientific basis was proposed before the middle of the eighteenth century. Following the dis-

* See page 103.

The Metcalf Photographic Refractor, 16 inches aperture, with accessory telescopes, at the Cambridge Station of the Harvard Observatory. With this instrument, which is used largely on studies of the structure of the Milky Way, more than 25,000 stellar photographs have been made.

covery of the satellites of Jupiter, and the satellites and rings of Saturn, the scientists of that time were able to note various consequences of the law of gravitation and the laws of motion that had been developed through the work of Kepler and Newton. Certain striking phenomena in the planetary system seemed to emphasize the fact that some single physical cause was back of the origin of the various planets.

Among others, the following conditions were observed: (1) all the planets travel in the same direction around the sun; (2) the sun and all the planets (then known) *rotate* in the same direction, and that direction (counterclockwise as seen from the north) is the same as the direction of common *revolution* around the sun; (3) the satellites (then known) travel their orbits in the same direction as the planets rotate; (4) all planets follow paths that are nearly in the same plane, and that plane differs little from the plane of the sun's equator.

In 1755 Immanuel Kant published his Universal Natural History and Theory of the Heavens, which contains the earliest definitely scientific statement of the Nebular Hypothesis. Laplace, too, conceived the solar system as condensing out of a vast extended nebula. In its primordial stages he considered it merely a rotating contracting mass of gas.

The hypothesis has been described in Chapter VI, and this is not the place to point

out in detail the obstacles to the somewhat comparable theories proposed by Kant and Laplace. Both suggestions were extraordinarily acute for their day, and they fail at the present time, not because more brilliant suggestions have been made, but because the advance of theoretical and observational astronomy gives us a better grasp of the problem.

As stated above, Laplace's model of sidereal evolution may be successfully applied to spiral nebulae, according to Jeans, and with modifications and extensions is more certainly applicable to the origin of double stars; but it fails to account for the planetary system. Kant's theory, which is, in important respects, allied with one of the cosmogonic theories of the Greeks, has also certain close resemblances in its broad outlines to the much later meteoritic hypothesis of Lockyer, and also to the planetesimal theory of the present time. In details, however, it fails to give a correct picture.

Planetesimal Hypothesis

About twenty-five years ago, inspired to some extent by the forms of spiral nebulae, Chamberlin and Moulton of Chicago University made an important step in the study of planetary origin by frankly abandoning all the older Nebular Hypotheses. They sought to derive the planets through the tidal disruption of the solar atmosphere. The passage of an-

other star was held to be the source of the disruption. After the passage of the disturbing star, the scattered material from the sun, called planetesimals, was supposed to have aggregated slowly into the planets, somewhat in the manner suggested by Kant.

A few important objections have been raised against the planetesimal theory. Astronomers, for instance, are now inclined to dissociate completely the spiral nebulae and planetary systems. The known spirals are on a much larger scale. Further, the majority of those geologists who are specially interested in the problems of genesis are inclined to doubt that the earth was built up from a very small beginning through the slow accretion of planetesimals. They favor the view that the earth in its early history was molten on its surface, and at that time probably had nearly the same mass as now.

The recent work on the planetesimal theory has been in the direction of theoretical details and of modifying the two most questionable points, that is, the association of planetary systems with spiral nebulae, and the importance given to planetesimals. Barrell, Daly, Jeans, and Jeffreys have taken the lead in developing the present form of the theory. Much remains to be done to complete the mathematical analysis, to harmonize all the relevant data, and to clear up many minor

points. As it stands we may summarize the hypothesis as follows:

At some time in the remote past, probably not less than three thousand million years ago, a star of greater mass than the sun came near. As it approached it raised on the sun two oppositely situated tides, such as the moon raises on the earth's oceans. The star passed within a few diameters of the sun, the distance necessary for the observed result depending upon the relative speed and mass of sun and star. Certainly the star did not collide with the sun, for the material thrown off, when the tides became too high and unstable, is but a small fraction of the sun's mass. The two tides changed into two streams of out-flowing gaseous matter. The ejected filaments broke into large pieces, gravitationally held together, but diverted in their outward motion by the attraction of the passing star.

Except for the transverse motion, produced by the passing star's attraction and possibly by the original solar rotation, most of the ejected material would have fallen back on the sun's surface. Presumably much of it did return to the sun, but at least eight of the ejected masses (the major planets) were sufficiently diverted that they henceforth cleared the solar surface when falling around the sun. From that moment they proceeded to move in elliptical orbits, the ellipticity gradually decreasing and the paths becoming nearly round

(as we find them today) through the retarding action of the resisting medium that was formed in the solar neighborhood by the smaller debris of disruption.

Origin of Moons

It has been suggested that when the major planets, moving in their original highly elongated paths, first returned to the vicinity of the sun, they too suffered a partial tidal disruption, such as the sun itself had experienced. The probable consequence of such planetary disruption by the sun is the birth of their major satellites.

Although the passing star was presumably also affected tidally, it could easily have escaped disruptive conditions, if its mass were much larger than the sun. We have no way, of course, of knowing what star is responsible for the solar family. If its motion relative to the sun were about the average for average stars, say twenty miles a second, and the motion remained uniform and directly away from the sun ever since the passage, its distance now would be of the order of three hundred thousand light years. There are thousands of millions of stars within that distance.

Probably in the early history of the planetary system, the earth's only satellite, the moon, was separated by fission from the earth itself. Jeffreys advocates the resonance theory, proposed and developed by G. H. Darwin. Accord-

ing to this explanation, the earth's primitive liquid body was set in unstable vibration, so to speak, by the near coincidence of its period of rotation with twice its natural free period. That is, in its early state, a bodily vibration of the earth would have a period of a little over two hours. Its rotation period at that time was probably between four and five hours, and a tide raised by the sun would recur every two hours, approximately. The combination of these two effects—the natural free vibration and the solar tides—probably resulted in piling up the magnitude of deformation beyond the critical point. At that moment the moon was born, and thenceforward, mainly as a result of tidal friction on the bottom of shallow seas, the rotation period of the earth increased until it is now twenty-four hours; and the moon receded from contact with the earth to its present distance of a quarter of a million miles. These two effects continue. The tides raised by the moon on the earth are very slowly decreasing the earth's rotational speed, and thus lengthening the day—but less than a thousandth of a second a century! At the same time the moon is receding from the earth, its mean distance increasing, however, only about seven feet in a century.

PART III

DIMENSIONS OF THE STELLAR UNIVERSE

XI

STAR FAMILIES

OUR solar system represents a simple kind of stellar family. Together with the double stars arising from rotational fission, it represents those associations that have been formed through the disruption of a single star. The gravitational organization of stars formerly independent of each other is another mode of forming stellar alliances. Still other groups, possibly illustrated by wide double stars such as ϵ Lyrae, or by globular clusters, may have been highly organized from birth, the assembling or differentiation having occurred in the ancestral nebula.

The Clustering Tendency

Because of these tendencies toward organization, it results that social relations among stars are nearly as common as among men and the lower animals. Sidereal bodies completely independent of all star societies are difficult

of conception; for both the heritage of early associations, and the immediate environment influence the present behavior and the destiny of stars.

Binaries and groups of three or four nearly equal bodies are thought to be very common—almost universal, it may be; and the assemblage of stars of all kinds by the tens, hundreds, and thousands into physically organized clusters now appears to be a property of fundamental significance in stellar investigations.

In considering the aspect of clustering among the stars we see a gradual progression from the largest and most scattered constellations to such rich and highly concentrated stellar groups as the globular clusters. Although the constellations were outlined for the most part in prehistoric times and have been used in myths and astrology persistently and universally through thousands of years, in general they do not represent definite physical organizations that exclude the stars of neighboring groups; and frequently even the legendary relationships of the stars in the most anciently known constellations are traced with difficulty.

There is, however, among the varied groupings, an easy transition from widely-scattered Ophiuchus and Camelopardalis to Orion, Scorpio, and the Great Bear; and in recent years we have found that the most conspicuous stars of these three last-named constellations

The stellar system Omega Centauri, one of the nearest of globular clusters.

actually form physically connected systems. The stars of each have motions, colors, and distances much in common, and in each case they have evolved, no doubt, from an origin common in space and in time.

From Orion we readily trace the progression in clustering to the Hyades—a more compact and more definitely circumscribed dynamical system—and then to the Pleiades, to Praesepe, to the double cluster in Perseus and similar faint loose clusters of the Milky Way; thence, by way of Messier 11 and Messier 22, we proceed by nearly equal steps to the typical globular system exemplified in the great Hercules cluster, Messier 13.

Open and Globular Clusters

Although we may justly restrict the term "star cluster" to physical systems—that is, to groups which have the characteristics of distinct dynamical organization—it is clear that the subdivisions of the long sequence of groups from Orion to the Hercules cluster must necessarily be vaguely defined. For convenience we here distinguish only open and globular clusters, and designate all as open except those ninety or a hundred highly condensed groups whose stars appear innumerable even with the aid to our biggest telescopes and most sensitive photographic plates.

Open and globular clusters differ in matters other than richness and apparent circularity.

In average distance from the earth the globular clusters much excel, in stellar constituency they are more varied, and we recognize in their wide distribution in space that from a dynamical point of view the globular clusters are quite distinct from the open groups which closely congregate along the middle line of the Milky Way.

A few of the nearest globular clusters are visible to the unaided eye as faint hazy objects, and some of them have been in the astronomical records for two or three hundred years. To Messier and earlier observers they were known as starless nebulosities, but Sir William Herschel and his son, with their greater telescopes, partially or completely resolved the brighter clusters into myriads of distinct stars.

The great telescopes of the present time and the powerful modern methods of astronomical investigation have greatly extended our knowledge of globular clusters, but they have not appreciably added to the total number. The numbers of known stars and nebulae have increased enormously with the increase of optical power, but during the last eighty years less than ten new globular clusters have been added to the original lists compiled by the Herschels. In fact, we seem to have passed the era of discovery of such systems; the present lists may be considered essentially complete—a condition that does not prevail for any other important type of celestial object.

It has been shown through the various studies made at Mount Wilson that most of the globular clusters are remotely isolated systems, neither intermingled with nor closely surrounded by other stars. They may be treated, indeed, as distinct cosmic units: moreover, they are much alike. In certain details, there are, to be sure, conspicuous differences from system to system; but in such matters as size, number of stars, and stellar make-up, no great diversity appears.

The case is very different for open clusters, for there we find diversity. Some are rich in many types of stars, others are confined, apparently, to one or two dozen stars with one special spectral characteristic. Some are only a few minutes of arc in diameter, while the outlying members of the Ursa Major group (the Big Dipper system) extend over the whole sky. Beta Aurigae, Alpha Coronae, Sirius, and other conspicuous stars belong to this widely spread cluster, a circumstance revealed by their motions in space along paths parallel to that of five of the Big Dipper stars.

Multiple and Double Stars

In passing, in this survey of star associations, from globular and open clusters to multiple stars, we have Castor and Alpha Centauri as instances of bright stars that are really systems composed of more than two components. Among the double stars we have good illustra-

tions of the two principal kinds in Sirius, a wide pair, and Spica, a close binary.

The close binaries, already mentioned several times, include the eclipsing variables, and the other products of tidal fission which might also be eclipsing stars if the planes of their orbits now happened to be more nearly in the line to the terrestrial observer.

The other kind of double star, the wide binary, is formed of components so distantly separated that tens, or hundreds, or even thousands of years are needed for a single revolution. They are sufficiently distant from each other that the components can be seen separately with suitable telescopic power. Many hundreds of these pairs are known. In exceptional cases they may have originated through the fission of a single star. In the opinion of the writer, they are more probably derived from earlier associations in highly condensed clusters.

The Local Star Cloud

Remembering that gravitational law prescribes that every particle of matter in the universe acts on every other particle, we naturally reason that the organizing tendency among stars, carried to its logical conclusion, would end in the organization of all stars into one system. Presumably such is the case, but we have not yet been able to see the total structure or trace out the motions of its parts.

The galactic system is an organization of stars and star clouds, nebulae and clusters. The star clouds in the Milky Way are sub-organizations in the general galactic system, each containing still smaller systems. There is doubtless a super-organization that includes both our own galaxy and other possible galaxies.

In the sub-structure of the Milky Way one part is of special interest. It is a local system, a sort of sub-galaxy. Some years ago, in a study of the distribution of the blue stars, Professor Charlier of Sweden called attention to the fact that the brighter stars of this class formed a flattened stellar system, two or three thousand light years in diameter. He considered the blue stars as forming a skeleton of the stellar universe, indicating its form and dimensions. Subsequently, the present writer showed that the B-star cluster is only a local phenomenon. Its dimensions and form are much as Charlier found, but its central plane does not coincide with the galactic plane; and far beyond its limits are many blue stars and clusters, and the faint stars of the Milky Way. This local cluster appears to be moving as a whole through a general field of galactic stars, the general field being a complex of innumerable loose clusters and indefinite star clouds.

Many of the stars surrounding the sun probably belong to the local cluster, and many to the general galaxy. To which the sun itself

belongs, we cannot say definitely, for both within the local cluster and without the stars have their individual motions in addition to the movement of the group to which they belong. The motion of the local cluster as a whole, and the systematic rotations and occultations within the group, are no doubt responsible for the phenomenon of "star streams" —the tendency (discovered twenty years ago by Kapteyn) for a large proportion of near-by stars to move in either of two opposite directions in the sky.

Summary

In summary of this chapter on star-families, we note that, although a comprehensive league of galaxies which would include Magellanic Clouds, spirals, globular clusters, and our galaxy is intimated by observed motions and distributions, the largest recognized organization is our galactic system. Its clusters and stars clouds are distinct though dependent units. One star cloud, a large flattened assemblage, surrounds the sun and is known as the local system. In its membership are loose clusters, such as the Pleiades and Hyades, which are organized systems of a lesser grade. In the Pleiades and other clusters, and among the stars at large, are numerous quadruple, triple and double systems. The simplest and smallest stellar family unit is the planetary system, of which we know only this one, but

assume many. Going still further toward small associations we may call attention to the moon-earth pair, and other planet-satellite groups, as organizations among the small secondary celestial bodies; and finally recall the meteor showers, which are composed of individual but associated particles of dust, moving through space under control of the same universal law that organizes the galaxy.

XII

MEASURING SPACE

THE most direct way of measuring the distance to the moon, sun, or nearby planet, is the method of the surveyor. A base line is measured on the earth's surface, and the direction, from the two ends of this line, to the body whose distance is sought, is determined with reference to some standard direction or point. With the base line and two angles known, an easy computation determines the distance. This method is simple and accurate when used to measure distances on the earth, but when applied to celestial bodies it is much complicated and rendered less certain by various factors—by the curvature of the earth's surface and its rotation and revolution, by the refraction in the earth's atmosphere, and the great distances involved. Other trigonometric methods, and methods depending on the velocity of light, and on the laws of planetary mo-

tion, have been developed, but cannot be described here.

Stellar Parallax

The surveyor's method is the one commonly used in obtaining the distance to the nearest stars. The base line used for stellar work is the diameter of the earth's orbit, a length of 185,000,000 miles. The parallax of a star is defined as the angle subtended, at the star's distance, by the radius of the earth's orbit, and is expressed in seconds of arc. The unit of distance,* a parsec, it will be remembered, corresponds to a parallax of one second and to a distance of 3.26 light years.

The more distant a star, the smaller its parallax and the greater the difficulty of angular measurement. Only the most accurate large photographic telescopes can find the parallax of a star three hundred light years away, although uncertain estimates are made for objects at twice that distance. American observatories have led in the work on trigonometric parallaxes, and observations in recent years from the Allegheny, Dearborn, McCormick, Mount Wilson, Sproul, and Yerkes Observatories have given fairly accurate distances for more than a thousand stars. This material has recently been collected at the Yale Observatory into a catalogue of parallaxes, which

* See Chap. II, p. 31.

also contains many of the values determined for the same stars by other methods.

Newer Methods

Realizing the limitations of the trigonometric method and the need of getting deeper into space if we are to comprehend much of the nature of the stellar universe, astronomers have long sought for new and more powerful ways of measuring the distances of individual stars. Statistical methods were devised for getting the average distances of groups of stars from their own motions and apparent magnitudes, but for any individual star the motion and brightness may deviate so greatly from the average values that the statistical method would give a very erroneous result. Moreover, the motions are not accurately known, except for brighter stars, and not at all for most of those fainter than the eighth magnitude.

In getting out farther than either the trigonometric or statistical method can go, necessity has again been the mother of invention, and within the last ten years a revolution in the measurement of stellar distances has developed. Formerly limited to a few hundred light years, we now measure distances of a hundred thousand light years and more. A few thousand stars are within the reach of trigonometric methods; the distances of millions have already been found since 1915 with the aid of the newer tools.

Actually the basis of the newer work lies in a very simple formula:

$$m - M = 5 \log d - 5$$

This equation expresses the relation between the apparent magnitude of a star, denoted by m, and its distance in parsecs d. The quantity M is the absolute magnitude (Chapter I) or real light emission. The apparent magnitude m gets fainter (numerically larger) for greater distances. The formula shows that $m = M$ when $\log d = 1$, that is, at a distance of 10 parsecs; for greater distances, the absolute magnitude is brighter than the apparent. For example, $M = 4.8$ for stars comparable with the sun in light emission. If photometric measurement shows that for such a star $m = 4.8$, then $m-M = 0$, and the distance must be ten parsecs. If $m = 14.8$, for a star comparable with the sun, we find in the same way that $\log d = 3$, and the distance is a thousand parsecs—a distance too great for trigonometric measurement.

The important quantity in the relation above is the absolute brightness M, for the quantity m is rather easily determined, and is already catalogued for a great number of stars. The recent advances in sidereal measurement have depended on development of methods of finding the real brightness of distant stars. The two principal methods were developed and applied mainly at the Mount Wilson Observatory, although much of the

necessary underlying observations and deductions had been made elsewhere, chiefly at the Harvard Observatory and by Hertzsprung and Kapteyn in Europe.

Absolute Brightness

I mentioned on an earlier page that the general inspection of the spectra of stars shows thousands to be similar to the sun. Spectral class may therefore be an indicator of absolute brightness. But sometimes giants and dwarfs are of comparable spectrum and color. Finer details and peculiarities in the spectra, however, show differences. The early work by Miss Maury at the Harvard Observatory, as later analyzed by Kapteyn and Hertzsprung, showed that certain giant stars had distinguishing marks that are not possessed by dwarfs. The subsequent work at Mount Wilson by Adams, Kohlschütter, and their associates, showed that various minor peculiarities could be used practically in some classes of stars, as criteria of absolute brightness. Intensive spectroscopic work improved the method and finally yielded absolute magnitudes for stars in most spectral classes and thus gave a means of solving the above simple formula for the distances of numerous stars far beyond the range of the surveyor's tools.

Here again we find that the spectroscope has made an important contribution to science. It has told us of temperatures, chemistry,

and velocities, and it now shows quantitatively the difference between giants and dwarfs of the same color, and thus gives the distance.

The physical reasoning back of these small differences in spectrum is as follows. A giant is brighter than a dwarf of the same spectral class because of its greater dimensions; its atmosphere is accordingly less dense, for the masses are much alike. The difference in atmospheric density affects the state of some of the radiating atoms, which reveal their condition through the intensity of their corresponding absorption lines in the spectra. The small spectral peculiarities are therefore an index of conditions in the stellar atmosphere, and consequently of stellar dimensions and stellar brightness.

Cepheid Variables

The second important way of determining the absolute magnitude and distance for remote stars, the so-called photometric method, is based on a relation between the periods and apparent brightness of the Cepheid variables —a relation found by Miss Leavitt, at Harvard, in her study of the Magellanic Clouds. In the course of a few months' examination of photographs made at the southern station of the Harvard Observatory, she found nearly two thousand variable stars. A few were studied in detail and found to belong to the

class of Cepheids, for which the light periodically brightens and fades. The Cepheids of long period in the Clouds were found to be brighter than those of short period. In fact, a definite numerical relation between the brightness and the period of variation was derived.

Further development of this work at Mount Wilson by the writer indicated clearly that the length of period for a Cepheid variable, wherever it might be, is almost always associated with a definite absolute brightness. In other words, by studying the variations of these variable stars sufficiently to derive the length of their periods and their apparent magnitudes, we can find their absolute magnitudes and compute their distances with the usual formula. This method is still more powerful than that based on spectral lines, for Cepheid variables can be discovered and studied when too faint and distant for spectroscopic work.

A more important use of the photometric method, however, is in connection with star clusters, for Cepheid variables are commonly found in such systems, and the determination of the distances of the variables gives at the same time the distances of the thousands of other stars in the clusters.

XIII

THE SIZE AND FORM OF THE MILKY WAY

THE systematic use of the new methods of measuring distance has taken us to all the parts of the galaxy where the absolute magnitudes of stars can be determined either from their spectra or from the period-luminosity law of Cepheid variation, or in other manners. The faint and very distant Milky Way star clouds have not yet been thoroughly explored, but are under investigation at a few observatories. The equally remote globular star clusters, however, have attracted wide attention, and the fortunate circumstance that many contain Cepheid variables has given them considerable prominence in cosmogony.

The distribution of the clusters with respect to the Milky Way plane shows that they are members of the same great organization that includes galactic clouds, the local system, and most of the known stars and nebulae. Half

of the globular clusters are north of the galactic plane and half are south of it. They are not found in the central part of the Milky Way (where open clusters are numerous), either because they are occulted by dark nebulosity, or because globular clusters entering that region have been broken up and transformed into open groups.

Distances of Globular Clusters

The first measure, a few years ago, of the parallax of a globular cluster, through the agency of its stars of deducible absolute magnitude, gave distances larger than we had commonly assigned to the diameter of the whole galactic system. The derivation of distances and positions in space for all globular clusters soon resulted in revising our estimates of the scale of the galaxy.

The two nearest globular clusters are in the southern sky, and bear the catalogue names of Omeba Centauri and 47 Tucanae. They are approximately twenty thousand light years distant. At that distance the angle subtended by the radius of the earth's orbit—that is, the parallax—is less than two ten-thousandths of a second of arc, and of course is quite beyond trigonometric determination. The well-known Hercules Cluster, Messier 13, is about thirty-six thousand light years away; and the distances of many of the most remote globular

clusters exceed a hundred thousand light years.

Form of the Galaxy

If our supposition is correct that the distribution of globular clusters is a clue to the form and extent of the galactic system, of which they certainly form a part, then we may obtain numerical values for the linear dimensions of the galaxy. Uncertainties must be admitted; we are not sure, for instance, what lies behind the dark nebulous curtains in many parts of the Milky Way. But keeping those doubts in mind, we can place the probable lower limit of the galactic diameter, along its central plane, at three hundred thousand light years.

The thickness cannot be closely estimated. As distances from the galactic plane increase, the stellar frequency appears to fall off rapidly. The majority of the stars are found within five thousand light years of the plane, but, occasionally peculiar variable stars and other objects of high velocity are found five or ten times this distance from the central plane. The globular clusters themselves are chiefly outside the thin central slice that contains the main body of galactic stars, but the open clusters and the gaseous and irregular nebulae are nearly all within.

The excessive flattening of the galaxy seems to be a common celestial phenomenon. It reminds us of the forms of some spiral nebulae,

of the local star-cloud, of the Ursa Major cluster, and of the planetary system itself. Also the planets and some of the stars are flattened at their poles through rotation. If we look more closely at the globular clusters, we find that they, too, are slightly flattened, apparently also as a result of rotation or through other dynamical causes.

XIV

ATTENDANTS OF THE GALAXY

THE isolated stars, as well as those in clouds and groups, stretch along the plane of the Milky Way for hundreds of thousands of light years, producing on the background of the sky the luminous galactic band. At right angles to the plane, in high galactic latitudes, the number of stars is relatively small, and a moderate sized telescope can show some objects on the very borders of the system. In certain directions in the Milky Way we have probably not yet reached bottom, but away from the galactic plane we seem to see through to the emptiness of cosmic space.

Nebulae of the Spiral Family

In these regions poor in stars we find numberless faint nebulae of the spiral family. Some actually show spiral arms, some are edge-on, some are oval and spheroidal. They are a rather mysterious type of object—not

fully understood. Either they are truly nebulous formations, or, as Kant and Herschel long ago suggested, they are other stellar systems and so remote in space that their individual stars in most cases cannot be resolved. In the writer's opinion, the latter view is correct, though the weight of some opposed evidence is admittedly high. Doubtless the matter will be definitely settled within the next few years, as astronomers are now actively concerned with the problem. Cepheids have been found by Hubble in the Andomeda Nebula and in other spirals, and if the testimony of such stars is thoroughly reliable in these circumstances, the nearest spiral nebulae must be about a million light years away; and some faint spirals must be at a distance of 100,000,000 light years.

If the bright spiral nebulae are at the edge of the galactic system, only a few thousand light years away, are they attendants of the Milky Way, or are they independent of its enormous gravitative power? The spectroscope at the Lowell Observatory in Arizona has been successfully directed to the measurement of the radial velocities of nebulae and clusters. The spirals as a class are found to be receding from the galaxy with enormous velocities. The average speed is something like four hundred miles a second, and the fastest goes at nearly three times this rate. Obviously, then, the spirals are not permanently

associated with the galaxy, for, with such speeds, in a short time (as time goes in the stellar universe) these objects will be invisibly remote.

But these measures of velocity may not represent real motion, especially if spiral nebulae are other galaxies. The apparent motions may be one of the important consequences of the theory of relativity, indicating the so-called curvature of space-time. A few years for observation and thought should also solve this problem.

Status of Globular Clusters

Whatever the status of the spirals, there are some objects that can be more definitely considered attendants of our galaxy. The velocities of globular clusters show that many, perhaps most of them, are falling toward the Milky Way. Though some are now well outside the galactic strata where most stars are found, their velocities are so high that in only a few million years they will be inside, mingling with the open clusters and star clouds. Even those clusters that are now receding from galactic regions must slow up as time goes on, for no doubt they are under the ultimate control of the galactic mass. Their distances and distribution seem to prove that point. A little later, perhaps in a hundred million years, they too may be coming in to

run a disruptive course through the galactic star clouds.

The globular clusters each contain tens of thousands of stars, perhaps hundreds of thousands. Their diameters are three or four hundred light-years—about the distance fróm the earth to the Pleiades. Thousands of stars in each cluster are giants, much brighter and larger than the sun. In fact, no star as faint as the sun has yet been photographed in a globular cluster; but the presence of such dwarfs in great number can be safely assumed.

Notwithstanding their large dimensions and masses, the globular clusters are small in comparison with our entire galaxy whose stars are to be numbered in unknown thousands of millions. The present writer has ventured the theory that the galactic system has been constructed out of the combination of such stellar clusters, and that dissolving groups like the Pleiades and the Big Dipper show one of the steps from the condensed groups to the scattered stars of the Milky Way. There certainly is good evidence that at present the Milky Way system is slowly absorbing the globular clusters, which only for the time being (a few billions of years) are attendants of the Milky Way.

Star Clouds

The large and small Magellanic Clouds are further examples of outside stellar systems.

Both of these important groups are receding with high velocity from the galactic plane Whether or not they succeed in completely divorcing themselves from its attraction is problematic, but further research may tell These Clouds are now under special investigation at the Harvard Observatory. Recently the distances of both have been determined, and many characteristics of their stars de duced. The Small Cloud has the parallax of 0″.000031, corresponding to a distance of a hundred thousand light years. The Large Cloud is about ten per cent more distant. These values are determined with much the same percentage of uncertainty as ten years ago we were deriving the distances of the stars one hundred light years away—an illustration of the progress that the oldest of sciences is making at the present time.

Knowing the distances of the Magellanic Clouds, we can determine the absolute magnitudes of their individual stars; and for those stars for which spectral classes are known, we can estimate the diameters. This procedure has led to the discovery of stars in the Small Magellanic Cloud that are brighter and larger than any heretofore found in the galactic system or in globular clusters. Some exceed the brightness of the sun twenty thousand times, and they have diameters so large that they would fill the orbit of Jupiter. These enormous giants probably are of large mass and

The Small Magellanic Cloud and the globular cluster 47 Tucanae. The cloud is about 100,000 light years distant, which is five times the distance to the cluster.

certainly of very low density. Some of them are variable stars. The most conspicuous are red stars like the giants Antares and Betelgeux, but much larger, of course, and brighter. In the Large Magellanic Cloud one ninth magnitude variable, S Doradus, is the most luminous object known, its emission being 600,000 times that of the sun. It radiates away 2,500,000,000,000 tons of its mass per second, but no doubt it will endure for at least trillions of years.

Another object that is outside the Milky Way and closely resembles the Magellanic Clouds is a faint star cloud bearing the catalogue number N. G. C. 6822. Discovered forty years ago by the famous Professor Barnard of the Yerkes Observatory, who at that time was an enthusiastic amateur observing with a six-inch telescope at Nashville, Tennessee, the star cloud has recently been analyzed by the photographic telescopes at Cordoba in the Argentine, at Mount Wilson, and at Harvard. To Barnard it appeared only as a nebulous mass. The most powerful of telescopes is required to bring out its stellar composition, for its brightest stars are fainter than the eighteenth magnitude. The distance has been estimated at 750,000 light years—making it one of the most remote objects known, and well beyond the limits of our galaxy as now discerned. Its diameter is comparable with that of the

Magellanic Clouds—perhaps five thousand light years.

Probably there are other remote star clouds like N. G. C. 6822, within the range of future study. Several objects of the sort are already suspected. There appear to be, in fact, all intermediate grades, both in structure and distance, between the Magellanic Clouds and the typical spiral and spheroidal nebulae. All these systems may be considered small or embryonic galaxies, or as island universes in limitless space.

XV

MAN'S PLACE IN THE SCHEME

IN CONCLUDING this rapid survey of modern developments, we may pause to consider again the place the earth holds in the general plan. We are, or should be, impressed by the general scope and dignity given to the evolutionary conception by the recent studies of astronomy and physical chemistry. Evolution is not limited chiefly to the relation of man to his anthropoid forebears. That phase is one of the minor steps in the development that pervades the whole universe. In truth, we cannot restrain the feeling that the whole of organic development, from the earliest one-celled protozoa to human consciousness and the higher hereditary instincts, is trivial and transient from the standpoint of the development of the material cosmos.

The sun, we have seen, is a dwarf star in the descending phase of its life history. The planetary system arose through the incidental passage of another star. Since that origin no

serious disturbance has occurred to sun and planets, either from passing stars or, since life appeared, from nebulosity of the Orion type, for the earth's geological history shows no great fluctuations in solar radiation.

The sun and its family are within a local cloud or cluster, but not at the center either of the local or the general system. One of the striking results of the study of clusters has been the demonstration that the sun appears to be extremely far away from the center of the galaxy. By taking the distribution of the globular clusters, novae, gaseous nebulae, and Milky Way clouds as a criterion of the form of the galaxy, it is found that the sun is about half way out toward the edge. The galactic center is in the direction of the southern constellation Sagittarius, and at a distance of sixty thousand light years or more. This eccentric position of the sun accounts for some of the irregularity of the Milky Way, and for the relatively greater richness, beauty, and importance of the southern stars and stellar systems.

These facts concerning position and dimensions indicate the humble place our species holds in space. The same condition obtains with regard to our place in time. Highly developed man—the type we call civilized—has been on the earth for only a fraction of the time necessary for the transit of light from a distant cluster. The whole time of existence

of organic life on the earth's surface, although it is now placed at the impressively large figure of a thousand million years or so, is short compared with the duration of a star, or with the time necessary to build a galactic system.

From our survey emerges an appreciation of the importance and magnitude of inorganic evolution—of the development from the simplest elements in the most primitive conditions, to the most complicated compounds of a planet or a meteor. Before animals and plants, the slow evolution of the earth's crust was necessary; before organic life, the cataclysmic origin of the planets occurred. Preceding that event, which was important for us but cosmically unimposing, the sun itself originated, and as a common star developed through its earlier spectral stages. The many inorganic phases of evolution seem infinitely to transcend the known animate parts in all ways, except, perhaps, in complexity.

So much for a sketch of the past. Speculation concerning the future is vain. But looking at the motions and structure of stars and nebulae, we of course see not the slightest reason for suspecting that they wait upon terrestrial organisms, or that they will all stop their evolution and cease to be when conditions on this planet become no longer favorable to the continuation of the delicately-balanced organic chemistry called life.

The future history of the stellar system appears, indeed, thoroughly independent of our temporary terrestrial career. Man's station in this scheme is not too flattering—an animal among many, precariously situated on the crust of a planetary fragment that obeys the gravitational impulses of one of the millions of dwarf stars that wander in remote parts of a galactic system. His place in the universe, from the standpoint of dimensions, duration, or physical influence, is unimpressive; and his importance in some non-material way is a subject not suited to scientific research or speculation. We leave the subject here, noting that man's rôle as an investigator and would-be interpreter of the universe is surpassingly fascinating, whether or not it is cosmically significant.

THE END

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